Bounds on DM interpretation of Fermi-LAT GeV excess

KC Kong and **J-CP** [arXiv: 1404.3741]

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THE UNIVERSITY OF KANSAS

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Santa Fe 2014 Summer Workshop

Higgs is discovered!

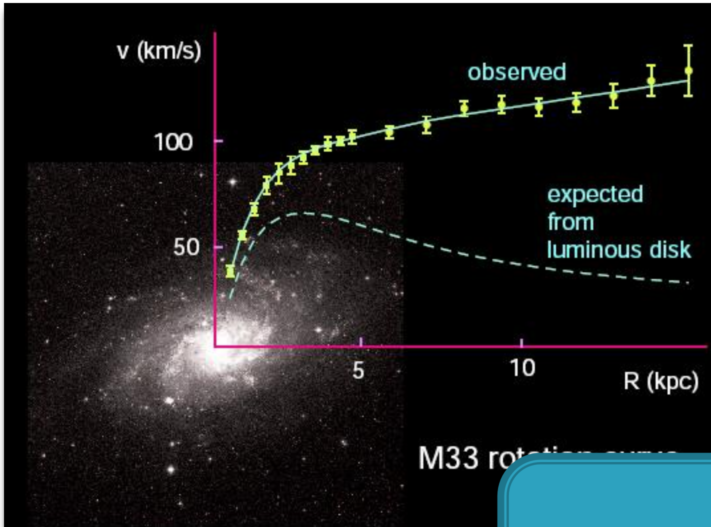
What is the next?

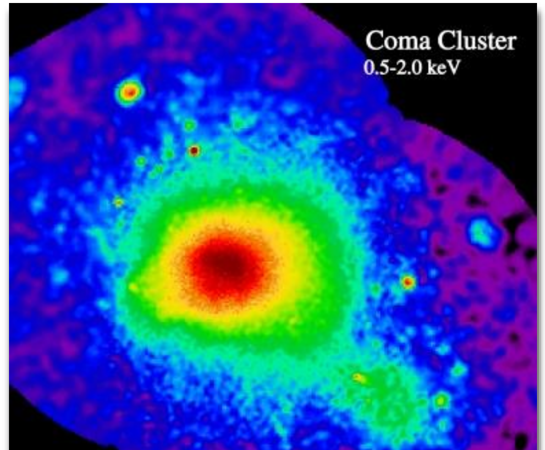
Dark Matter?!

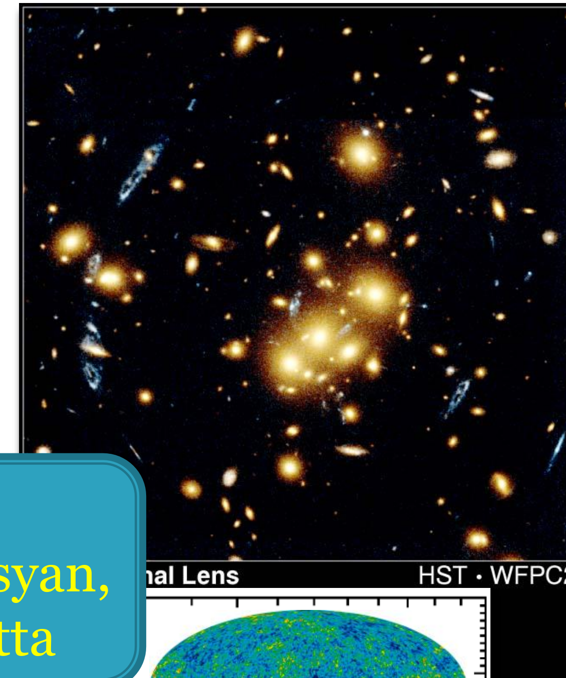
Dark matter

- discovered via gravity

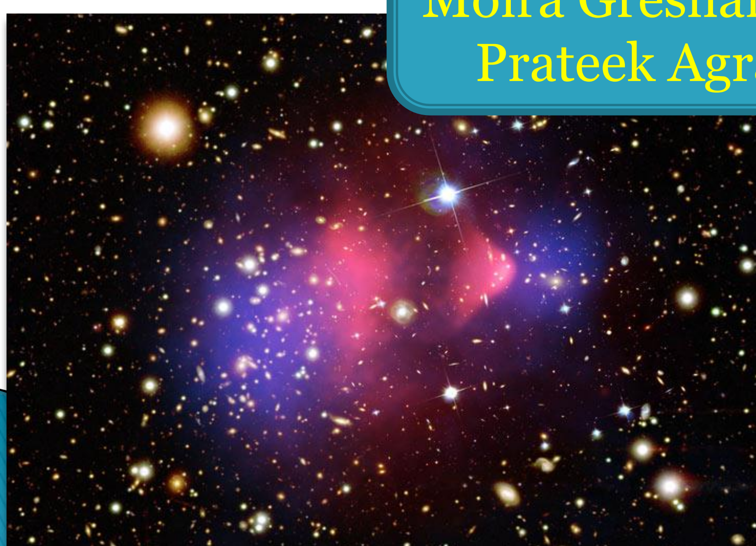
  by Fritz Zwicky (1933) & Vera Rubin (1970)

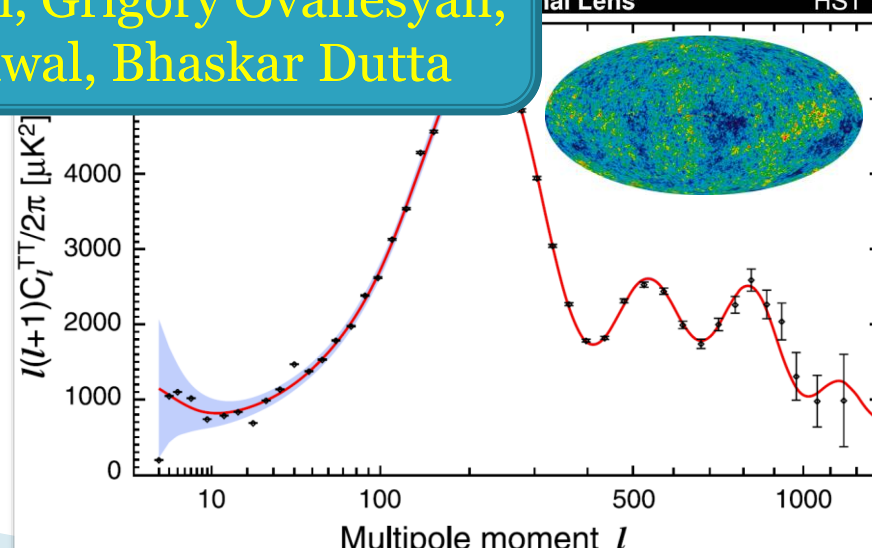






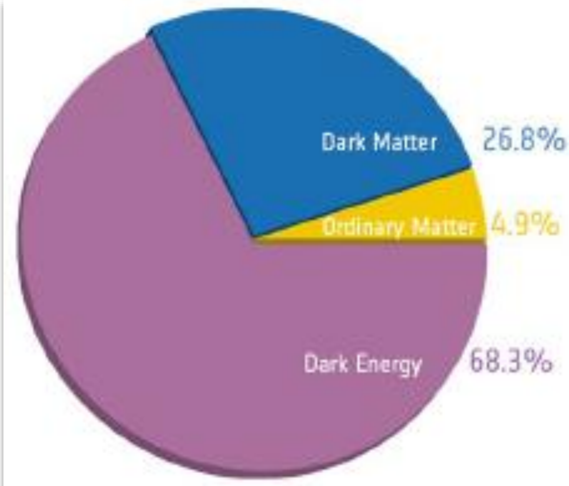
Talks:
Moira Gresham, Grigory Ovanesyan,
Prateek Agrawal, Bhaskar Dutta

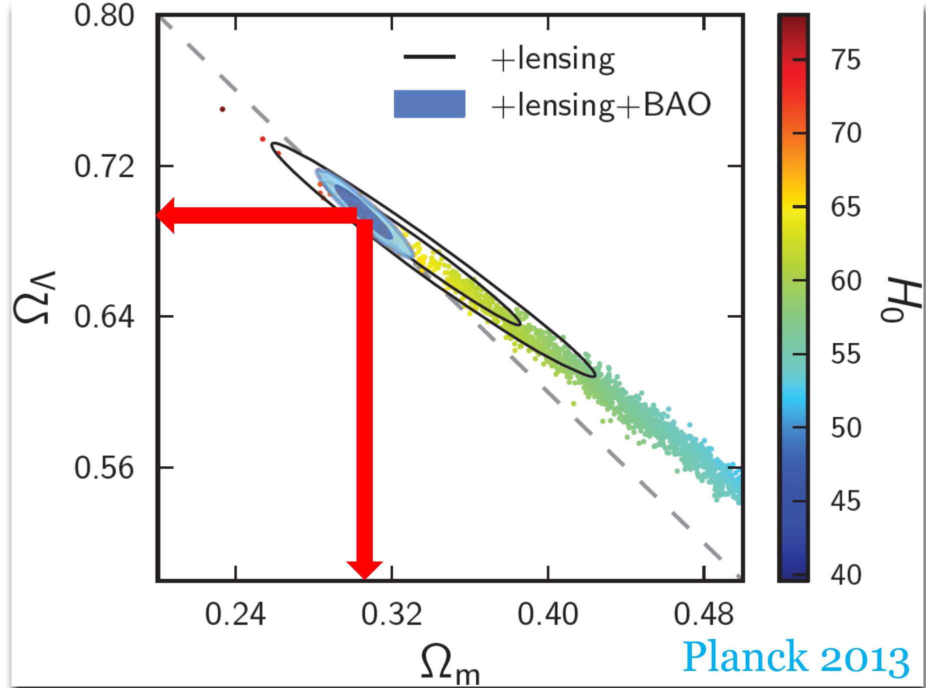




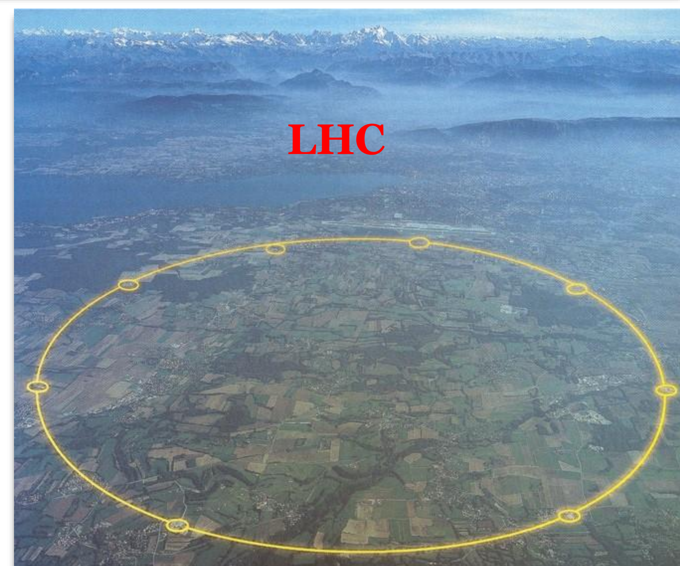
And ...

❖ DM accounts for 1/4 of the mass-E of the Universe.





❖ For the particle identification, a discovery via EM, strong or weak probes is needed: e.g. DM direct detection, production, etc.



Outline

- DM indirect searches
  - → GeV γ-rays from the Galactic center
- Constraints:
  - ✓ Indirect detections
  - ✓ Direct detections
  - ✓ Colliders
- Conclusion

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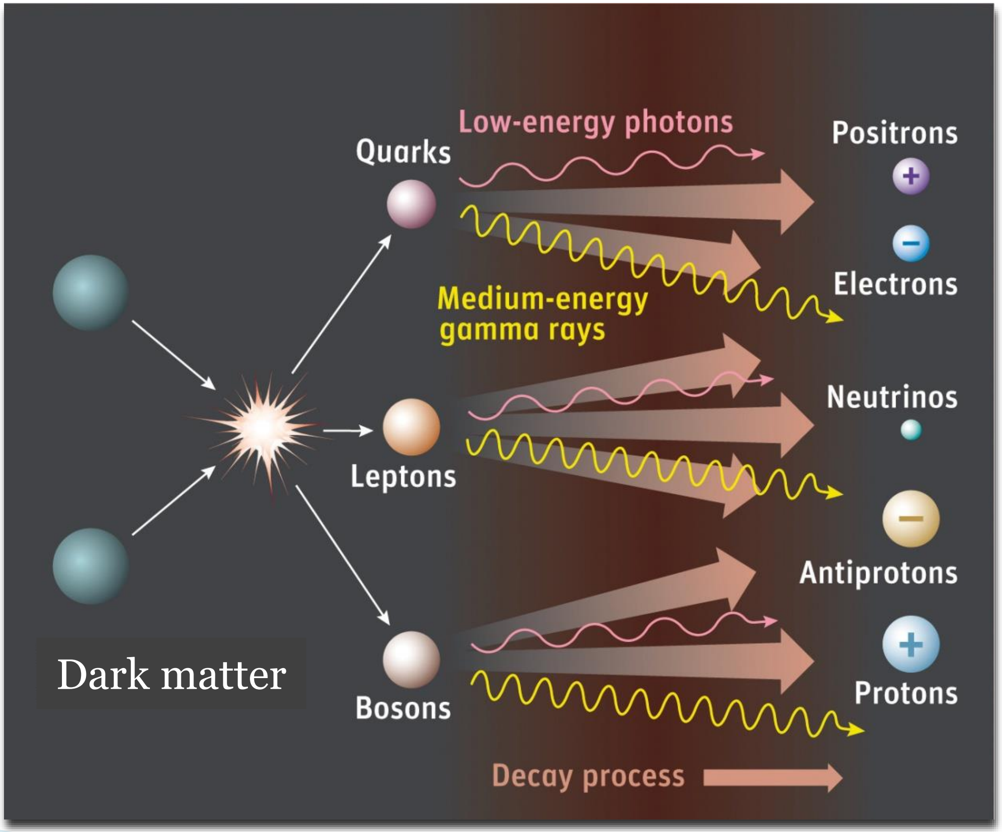
Indirect detection

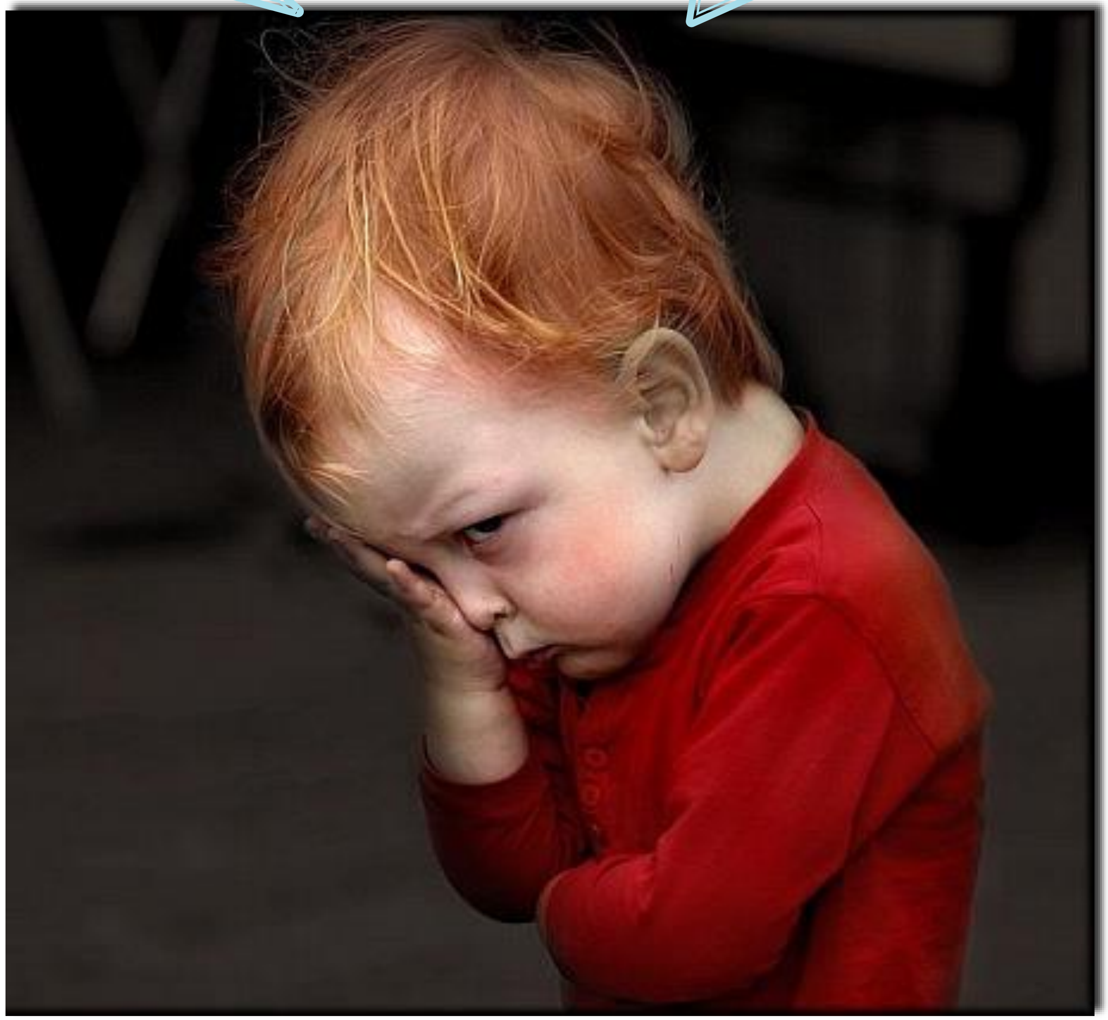
- ❖ Indirect detection experiments search for the products of DM annihilation or decay: gamma rays, neutrinos, positrons, and antiprotons
- ❖ Not conclusive evidence since the backgrounds from other sources are not fully understood.



- ➢ 130 GeV
- ➢ O(GeV)
- ➢ 511 keV
- ➢ 3.5 keV
- ➢ e^+
- ➢ …

DM signals?

Um… Well…



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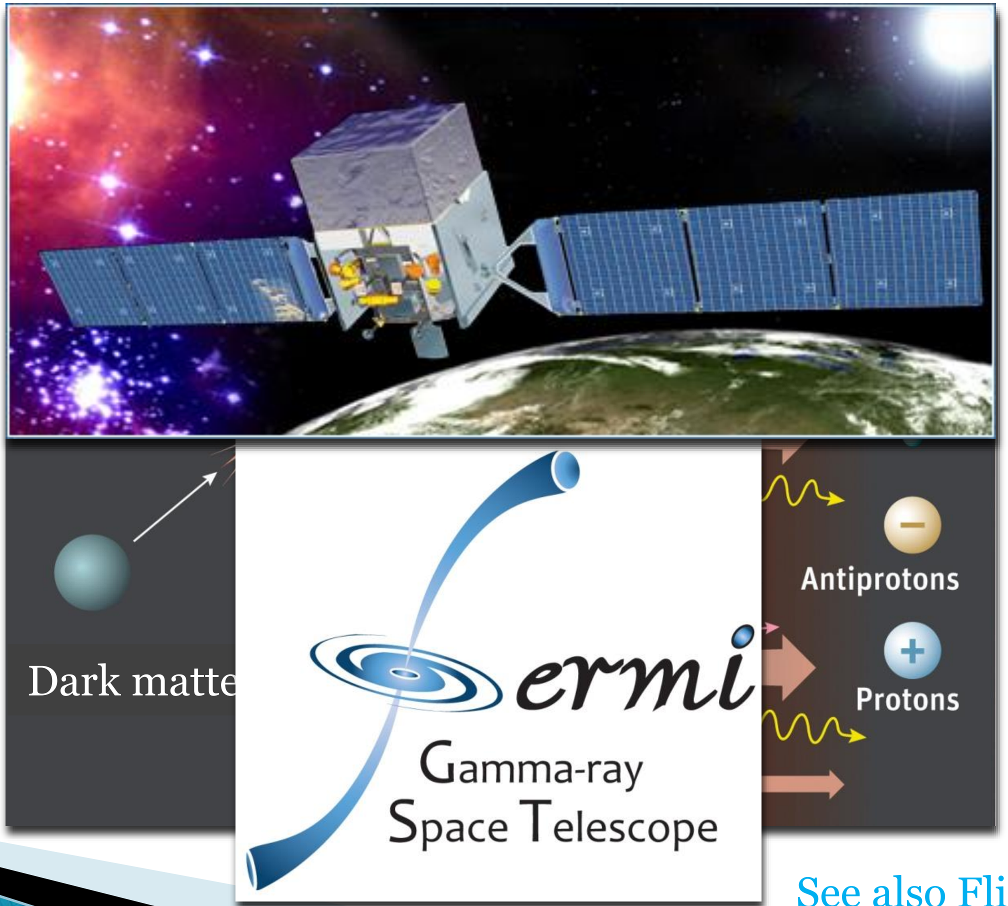

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- ➢ …

See also Flip Tanedo's (Friday)

History of Fermi-LAT GeV excess

- L. Goodenough & D. Hooper, arXiv:0910.2998 (1 year)
- D. Hooper & L. Goodenough, arXiv:1010.2752 (2 year)
- D. Hooper & T. Linden, arXiv:1110.0006 (
- K. Abazanjian & M. Kapli
- D. Hooper & T
- C. Gordon & O. 306.5725
- W. Huang, A. Urbano & W. Xue, arXiv:1307.6862
- K. Abazanjian, N. Canac, S. Horiuchi & M. Kaplinghat, arXiv:1402.4090
- T. Daylan, D. Finkbeiner, D. Hooper et al., arXiv:1402.6703
- ...

Hooperon !

The Signal:
Gamma Rays from Dark Matter

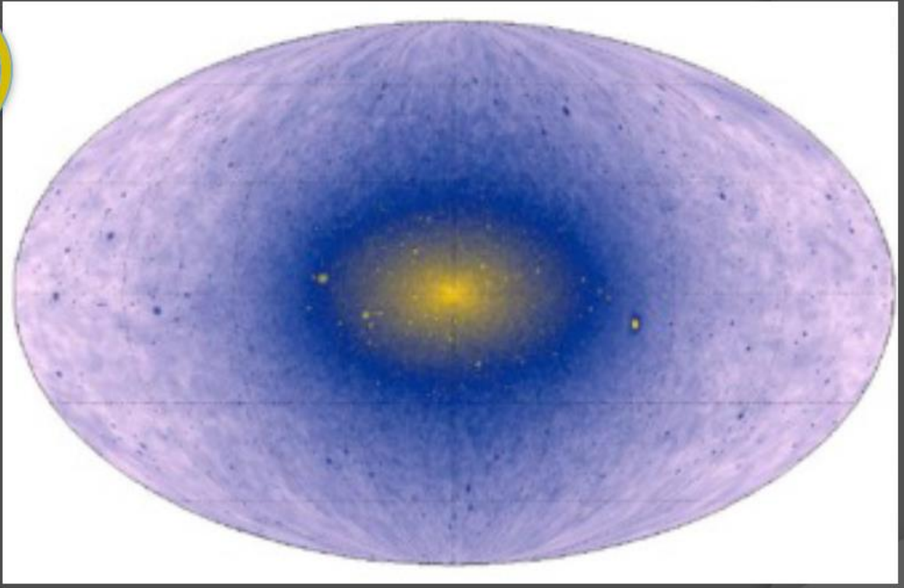
The gamma-ray signal from dark matter annihilations is described by:

$$\Phi_\gamma(E_\gamma,\psi) = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\frac{\langle\sigma v\rangle}{8\pi m_X^2}\int_{\mathrm{los}}\rho^2(r)\mathrm{d}l$$

1) Distinctive "bump-like" spectrum

2) Normalization of the signal is set by the dark matter's mass and annihilation cross section (in the low-velocity limit)

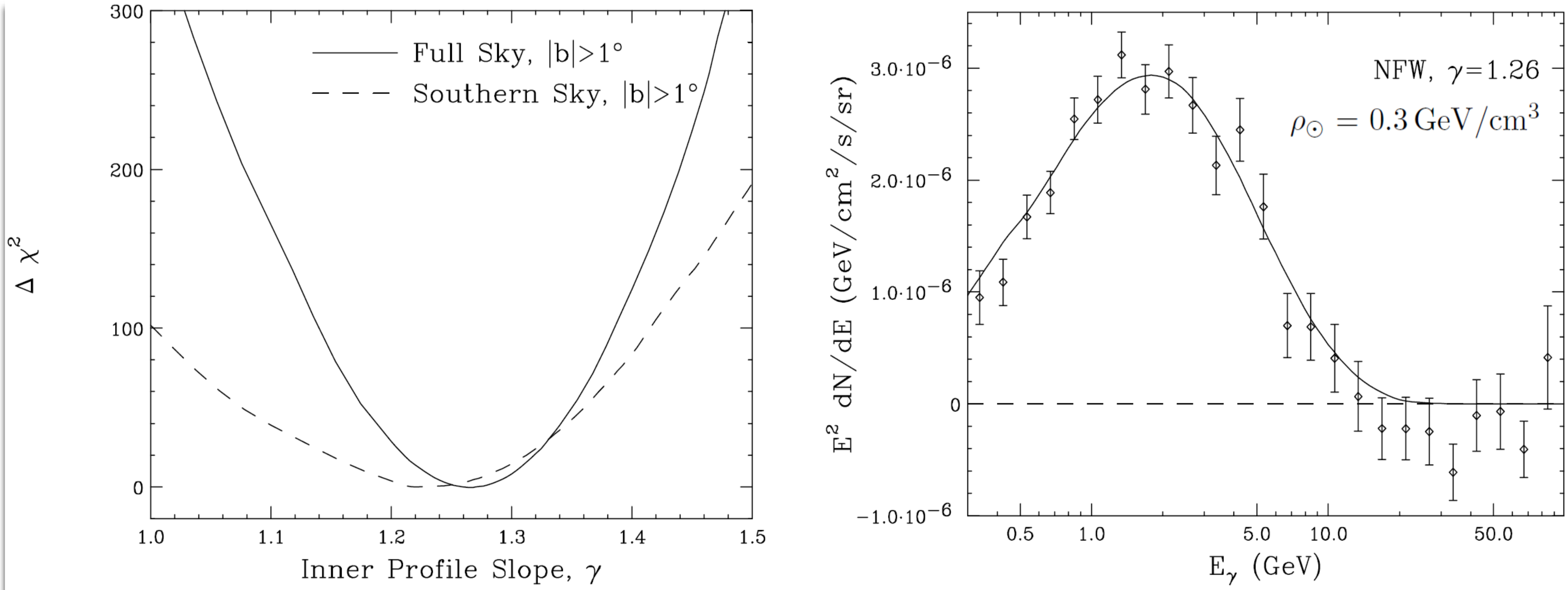
3) Signal concentrated around the Galactic Center (but not point-like) with approximate spherical symmetry; precise morphology determined by the dark matter distribution



M. Kuhlen *et al.*

Features of GeV excess I

arXiv:1402.6703



- The excess is distributed around the GC with a flux falling off as $\sim r^{-2.5}$.
- The spectrum of the excess peaks at 1-3 GeV.

Features of GeV excess I

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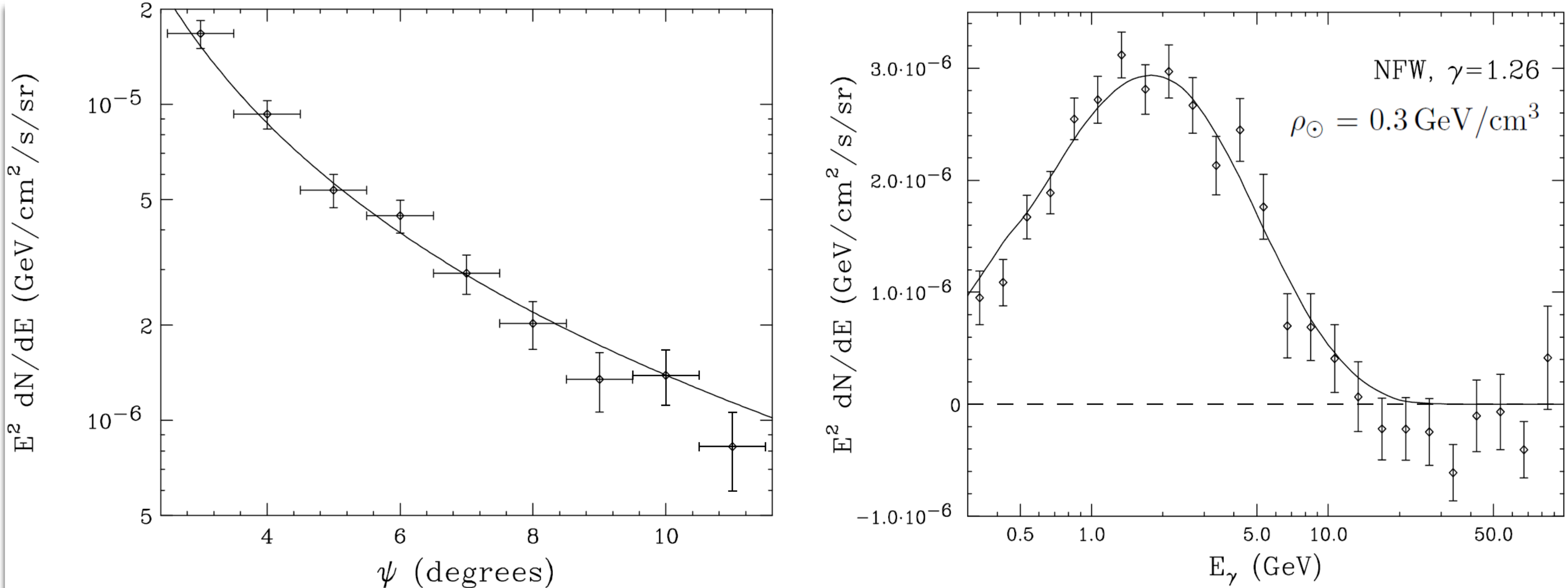
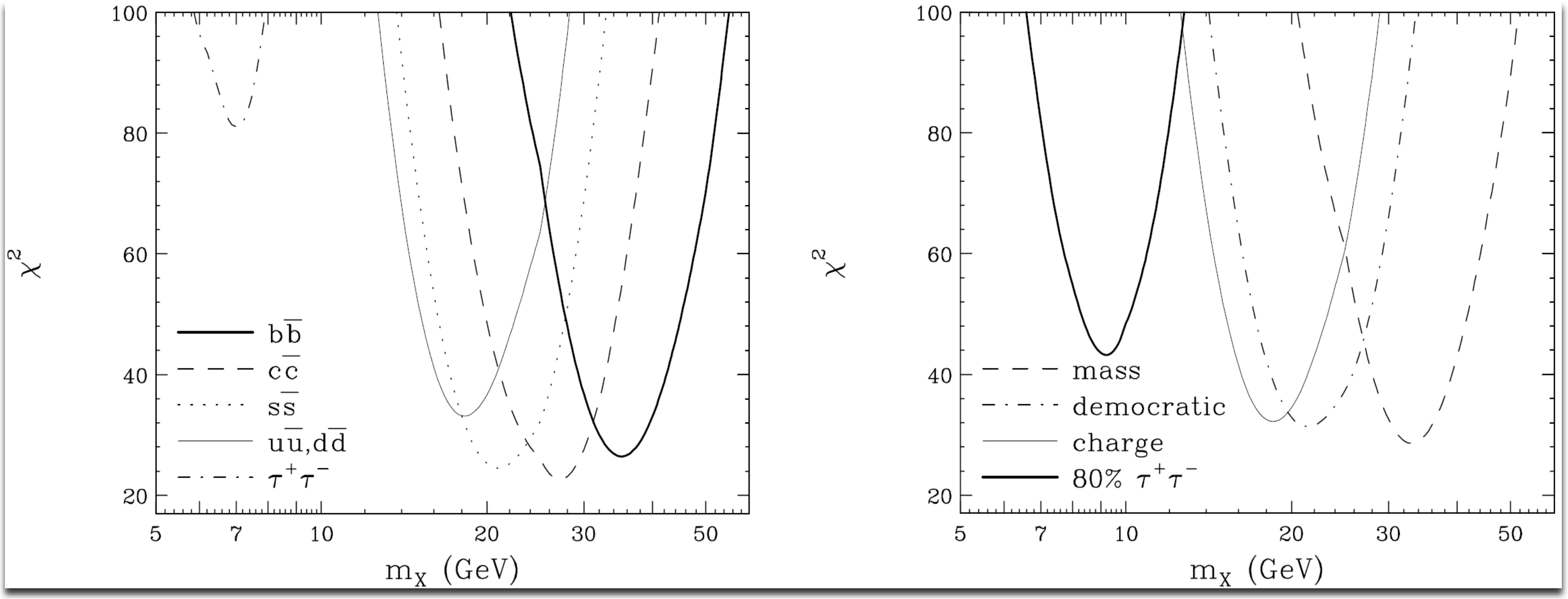


- The excess is distributed around the GC with a flux falling off as ~$r^{-2.5}$.
- The spectrum of the excess peaks at 1-3 GeV.
- Signal is extended to > 10^{o} from the GC → disfavor millisecond pulsars
- Consistent with the dynamical center of the Milky Way

Features of GeV excess II

arXiv:1402.6703



❖ The spectrum is in good agreement with the predictions from 20-40 GeV DM annihilating to mostly quarks.

Features of GeV excess II

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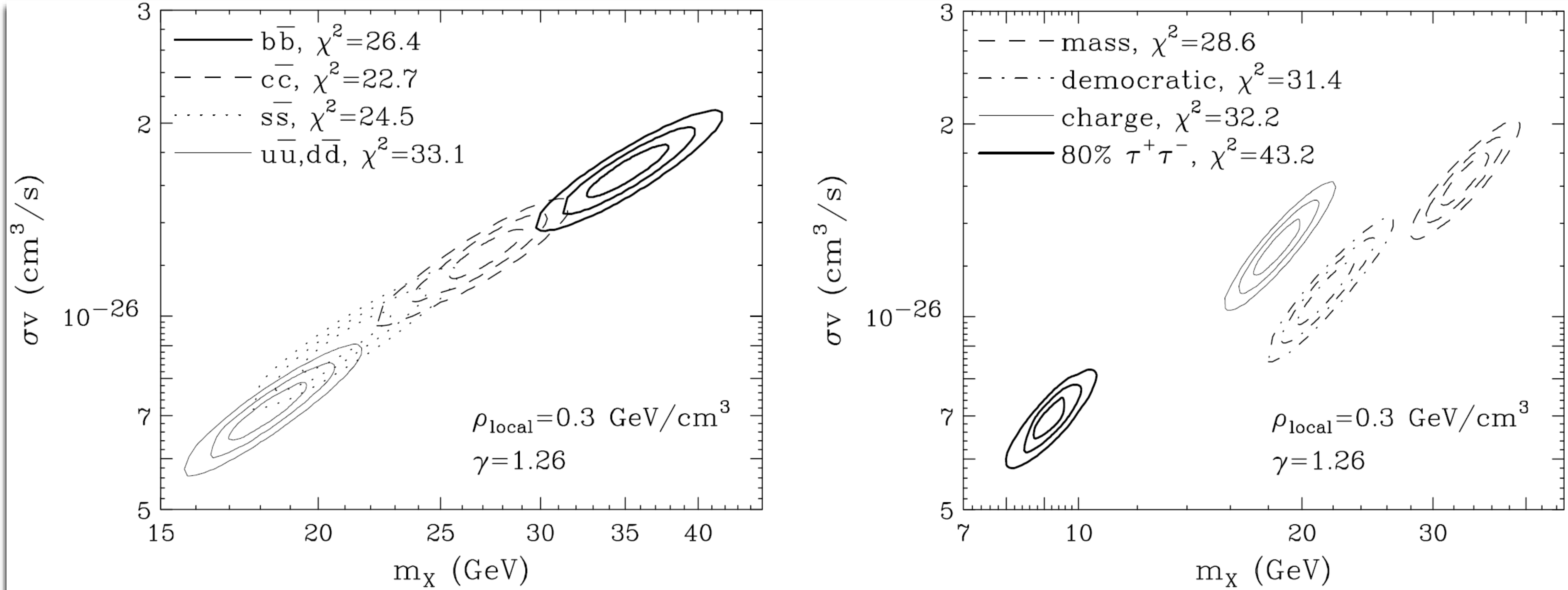
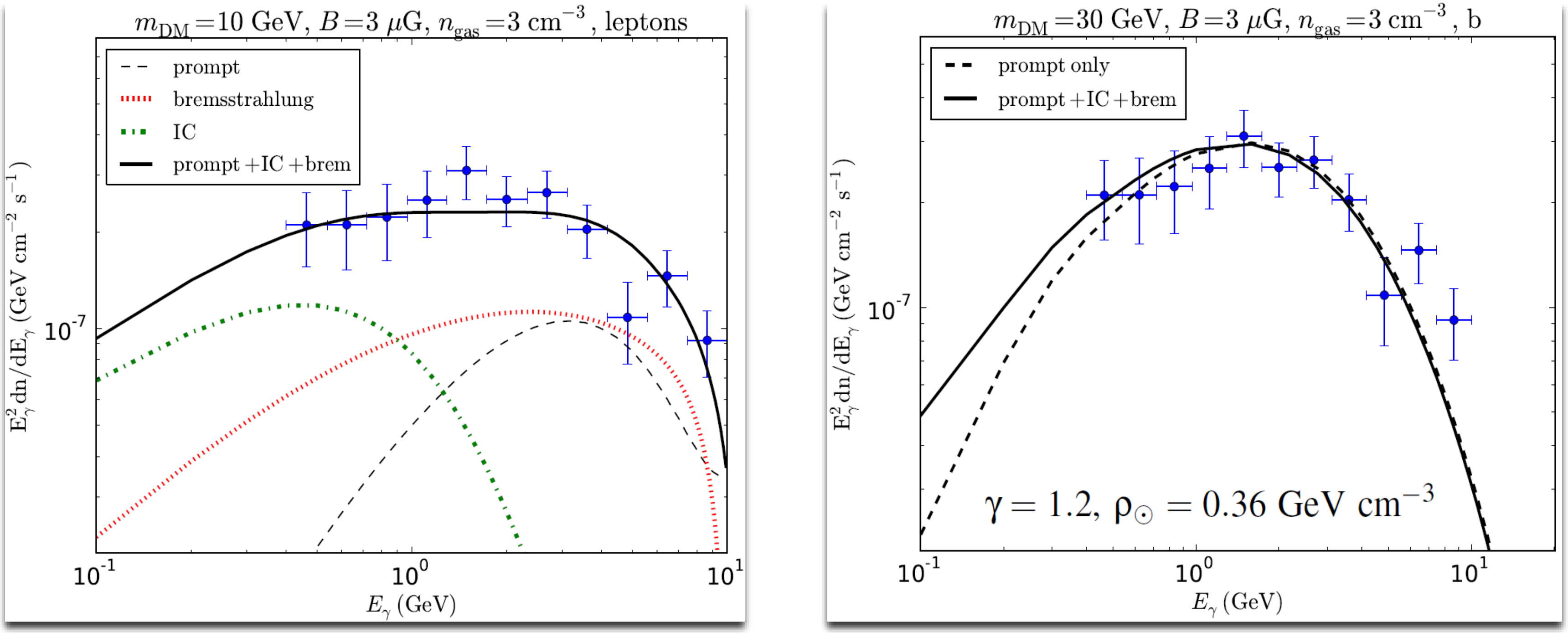


- The spectrum is in good agreement with the predictions from 20-40 GeV DM annihilating to mostly quarks.
- Required cross section is ~1-2 · 10^{-26} cm^3/s

Features of GeV excess III



- T. Lacroix, C. Boehm & J. Silk (arXiv:1403.1987) point out that a contribution of the diffuse γ from primary and secondary e's is significant, especially for leptons.
- With the IC and Bremsstrahlung contributions, ~10 GeV DM annihilating into leptons provide a little better or similar fit to the pure b-quark state.

Summary of GeV excess

- Leptons: poor fit ← w/o IC & electron diffusion for Bremsstrahlung
- Quark final states: $\langle\sigma v\rangle_{qq}$=(1-2) · 10^{-26} cm^3/s for m_{DM}=20-40 GeV depending on quarks.
- DM > millisecond pulsars ← signal is extended to > 10^o from the GC

arXiv:1402.6703

- Pure leptons (e:μ:τ=1:1:1): $\langle\sigma v\rangle_{ll}$=0.86 · 10^{-26} cm^3/s for m_{DM}=10 GeV
- Pure b-quarks: $\langle\sigma v\rangle_{bb}$=2.03 · 10^{-26} cm^3/s for m_{DM}=30 GeV

  cf. w/o diffusion & IC, $\langle\sigma v\rangle_{bb}$=2.2 · 10^{-26} cm^3/s
- Diffusion model induces an additional uncertainty (MIN, MED, MAX)

  → $\langle\sigma v\rangle_{ll}$=(0.68-1.18) · 10^{-26} cm^3/s

arXiv:1403.1987

DM models for GeV excess

- GeV excess & direct detection signals: B. Kyae & **JCP** (1310.2284)
- Flavored DM: C. Boehm, **Matthew Dolan** et al. (1401.6458),

  Prateek Agrawal, B. Batell, D. Hooper & **Tongyan Lin** (1404.1373), …
- Effective Ops.: W. Huang, A. Urbano & W. Xue (1310.7609)

  A. Alves, S. Profumo, F. Queiroz & W. Shepherd (1403.5027),

  A. Berlin, D. Hooper & S. McDermott (1404.0022),

  E. Izaguirre, G. Krnjaic & B. Shuve (1404.2018), …
- Cascade annihilation: C. Boehm, **Matthew Dolan** & C. McCabe (1404.4977),

  P. Ko, W. Park & Y. Tang (1404.5257), **Arvind Rajaraman** & **Philip Tanedo** et al. (1404.6528), A. Martin, J. Shelton & J. Unwin (1405.0272), …
- …

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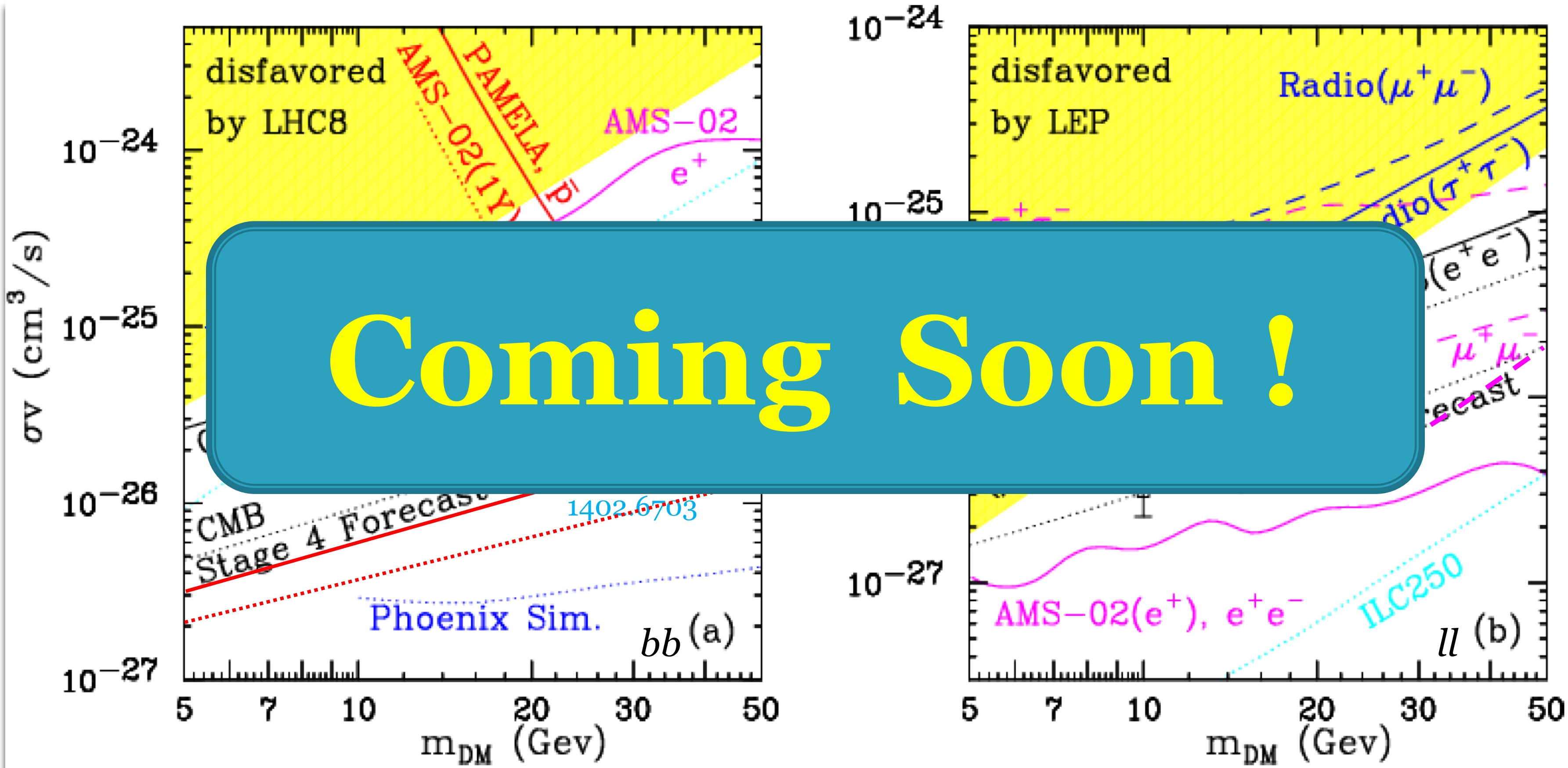
The goal!

K.C. Kong & JCP,
arXiv:1404.3741



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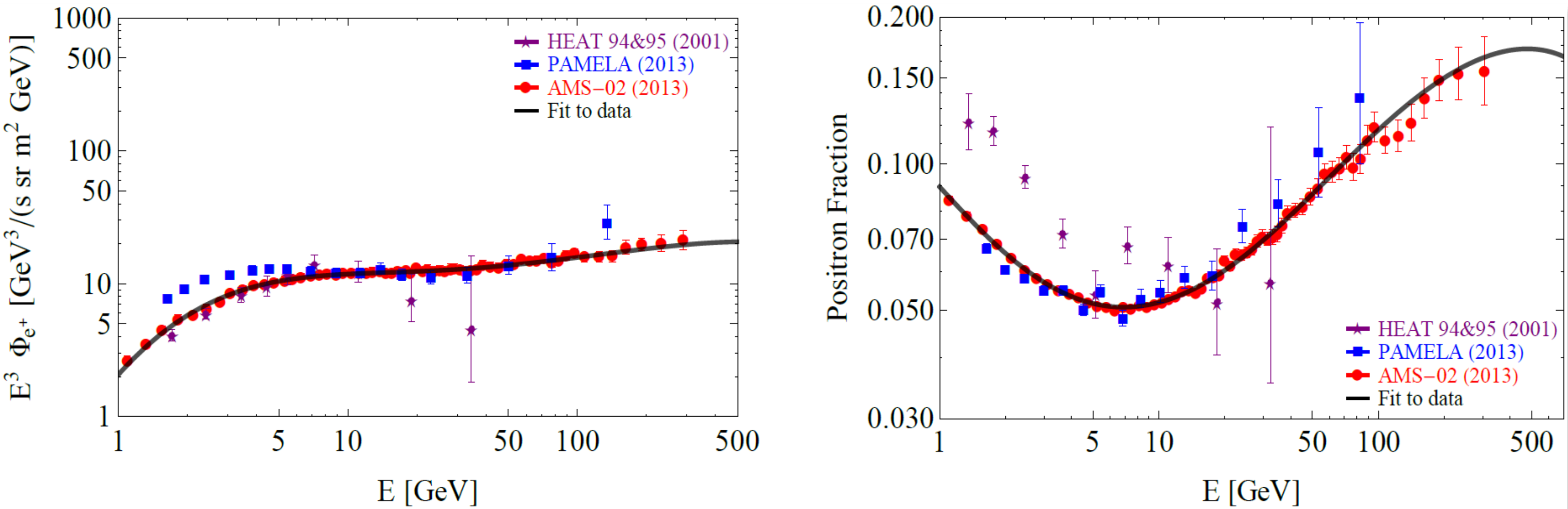
Indirect detection: e⁺ I

Ibarra, Lamperstorfer & Silk, arXiv:1309.2570



- Precise measurements of cosmic e⁺ by AMS-02 → constraints on DM
- Reasonable BG model considering a possible primary astrophysical origin
- Total interstellar e⁺ flux: $\Phi_{e^+}^{\mathrm{IS}}(E) = \Phi_{e^+}^{\mathrm{sec,IS}}(E) + \Phi_{e^+}^{\mathrm{source,IS}}(E) + \Phi_{e^+}^{\mathrm{DM,IS}}(E)$
- χ^2: pure BG model vs BG + DM annihilation

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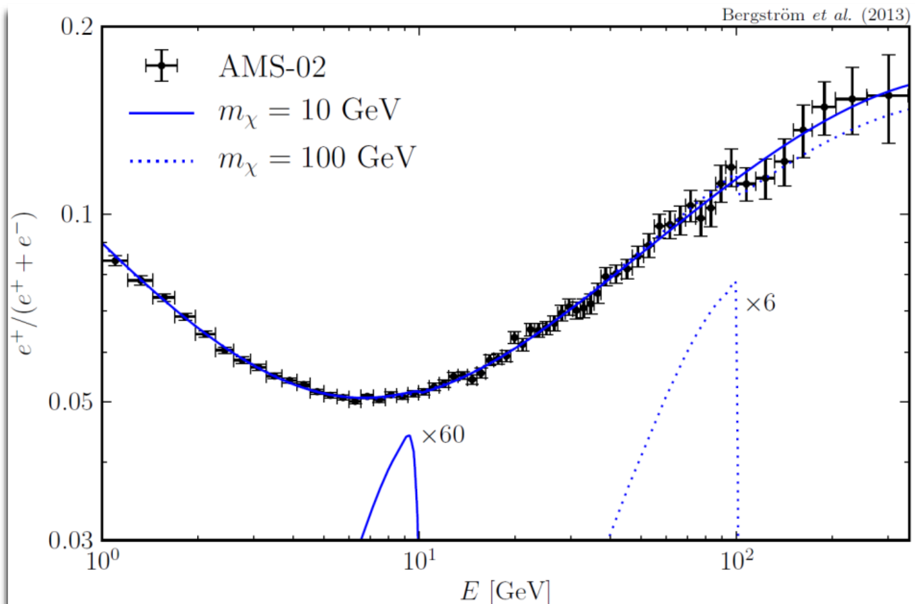

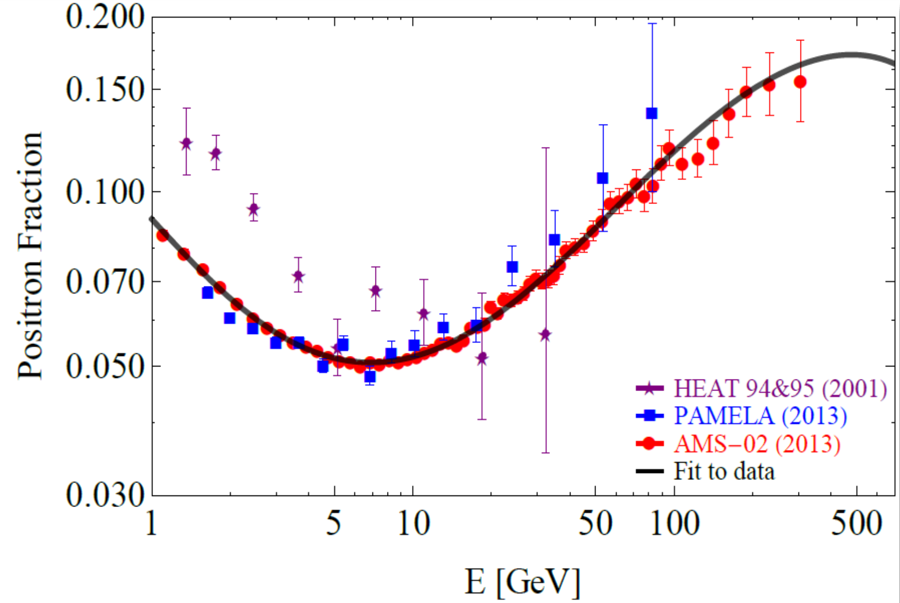

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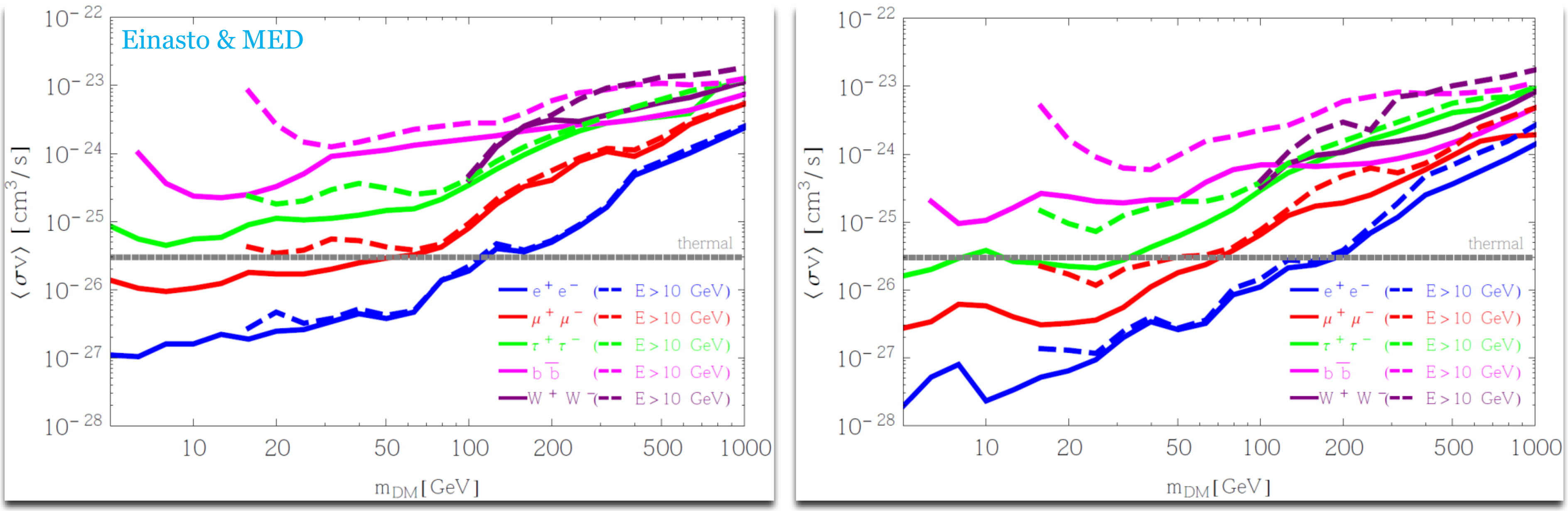
Indirect detection: e^+ II

Ibarra, Lamperstorfer & Silk, arXiv:1309.2570

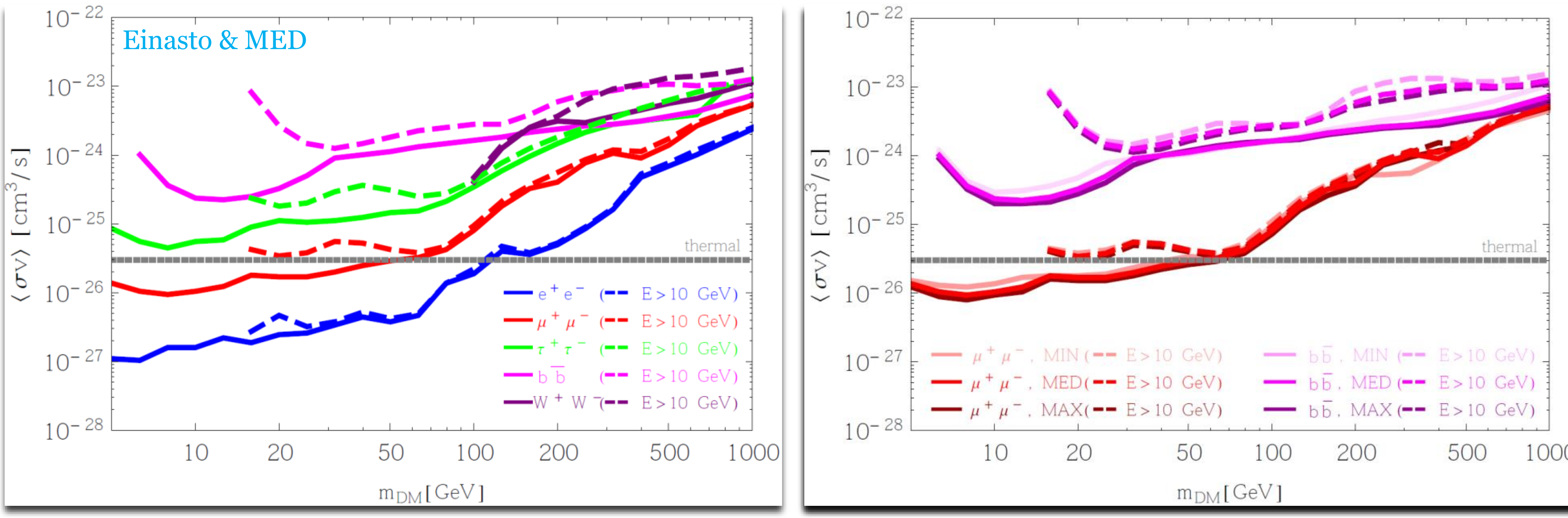


❖ Limits on <σv> from e^+ flux (left) and fraction (right):

Those from e^+ flux are comparable or weaker, especially in low m_{DM} region.

Indirect detection: e^+ II

Ibarra, Lamperstorfer & Silk, arXiv:1309.2570



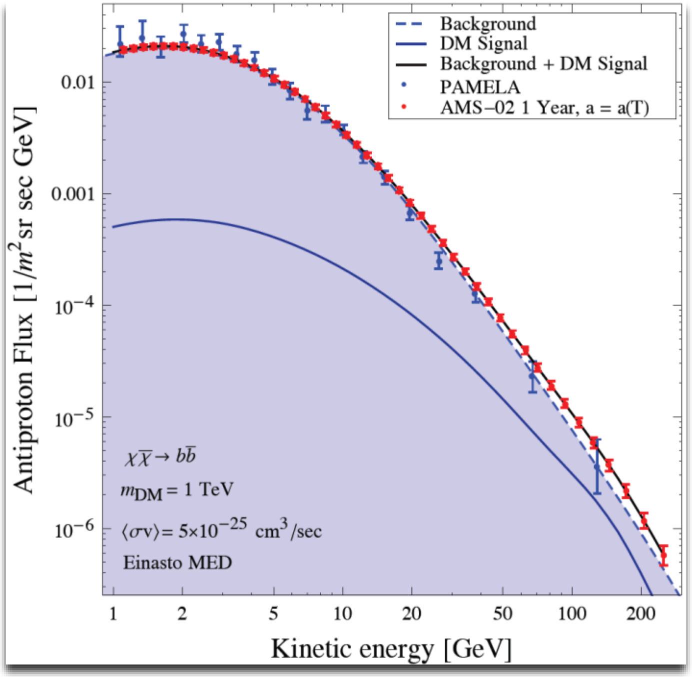
- Limits on <σv> from e^+ flux (left) and fraction (right):

  Those from e^+ flux are comparable or weaker, especially in low m_{DM} region.

- MIN & MAX propagation parameter sets as well as NFW & isothermal profiles → limits are just mildly affected.

Indirect detection: anti-p I

Cirelli & Giesen, arXiv:1301.7079



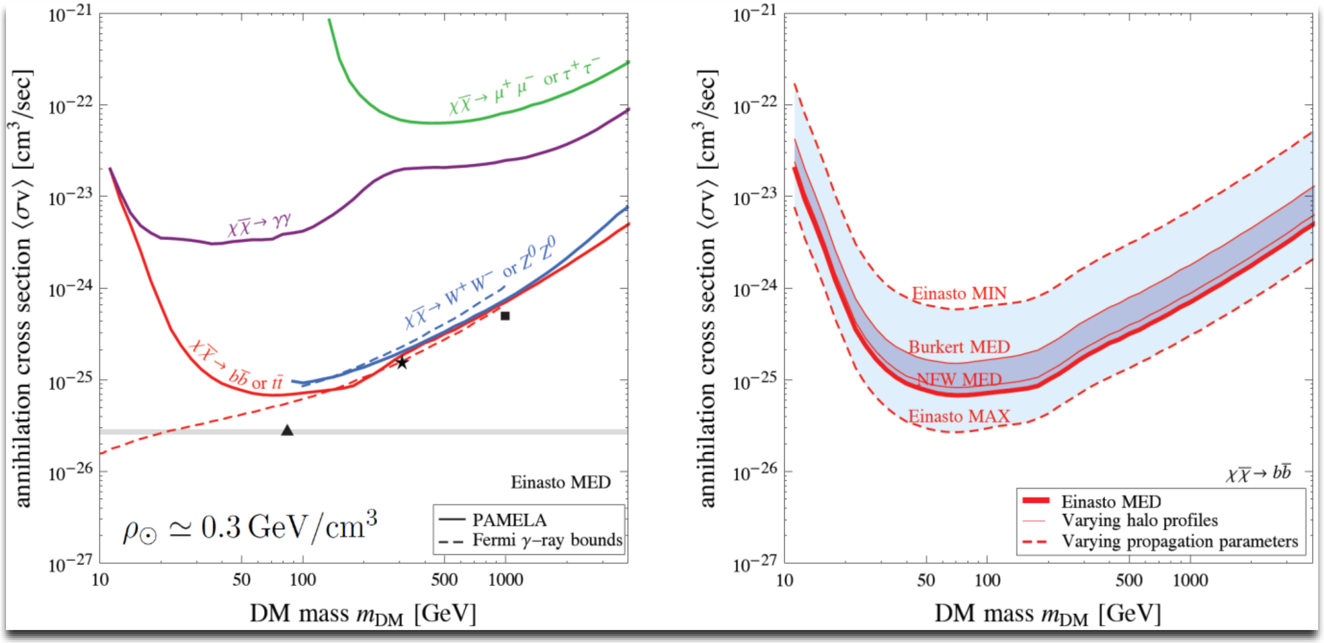
- Anti-p is generic for hadronic or gauge boson annihilation channels.

  → constrained by current PAMELA & upcoming AMS-02 results on anti-p

- Astrophysical BG by cosmic-ray processes is optimized within the uncertainty to minimize the χ^2 of the total anti-p flux.

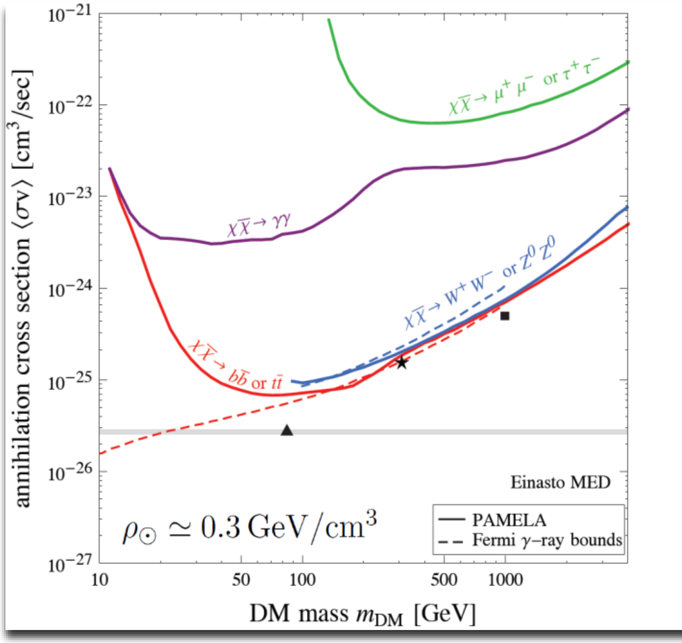
Indirect detection: anti-p II

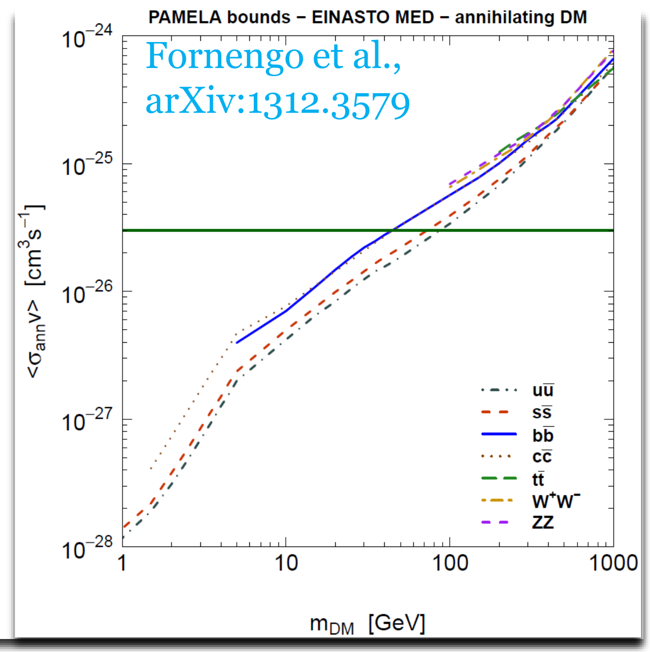
Cirelli & Giesen, arXiv:1301.7079



- Constraints on <σv> from anti-p flux & astrophysical uncertainties
- Almost same for NFW, 2-3 times weaker for Burkert
- ~10 times weaker for MIN, 2-3 times stronger for MAX

Indirect detection: anti-p II



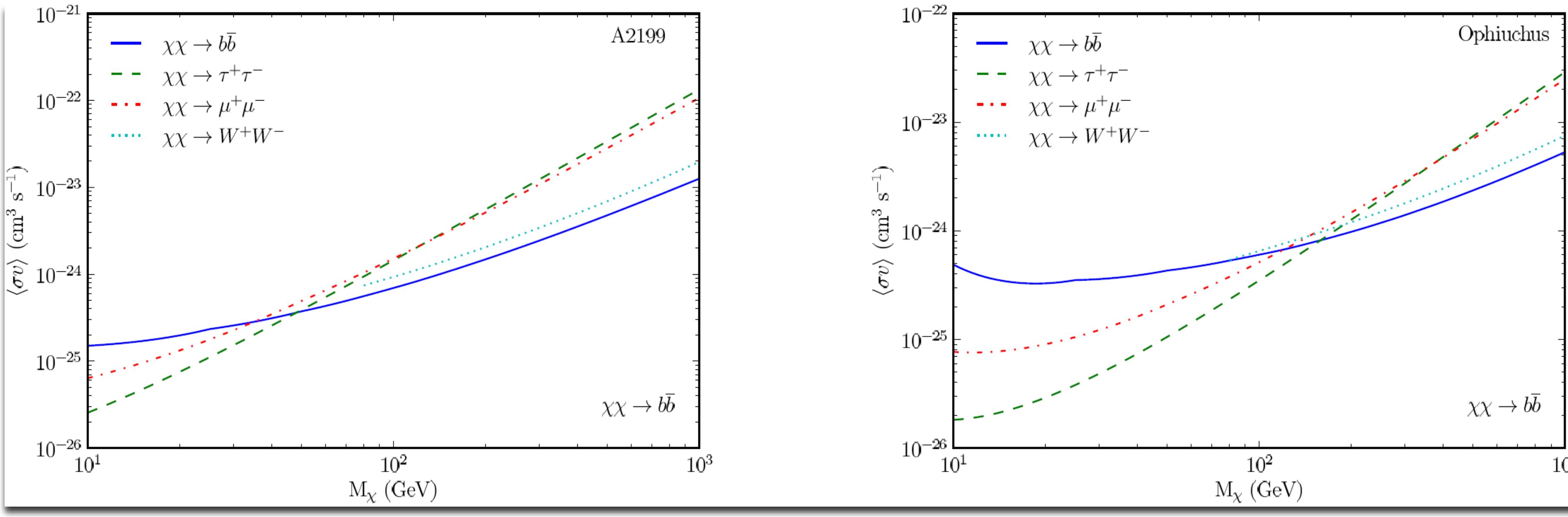


Cirelli & Giesen,
arXiv:1301.7079

- Constraints on <σv> from anti-p flux & astrophysical uncertainties
- Almost same for NFW, 2-3 times weaker for Burkert
- ~10 times weaker for MIN, 2-3 times stronger for MAX
- With the data of E<10 GeV including the solar modulation effect

Indirect detection: radio I

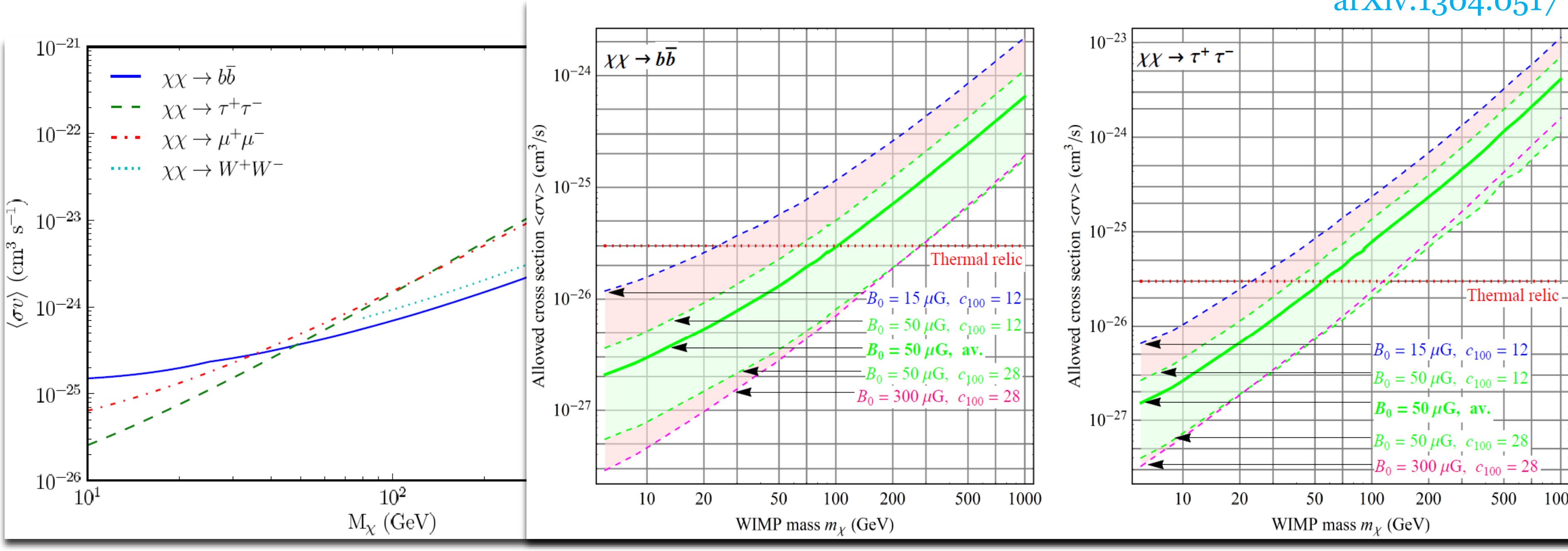
Storm, Jeltema, Profumo & Rudnick arXiv:1210.0872



- Relativistic e^- & e^+ lose E via synchrotron radiation → bounds on <σv> using limits on the diffuse radio emission from nearby galaxy clusters
- Smooth NFW profile for ~ 10 galaxy clusters: comparable results for different clusters.
- Galactic center: similar limits. (arXiv:1002.0229)

Indirect detection: radio I

arXiv:1304.0517



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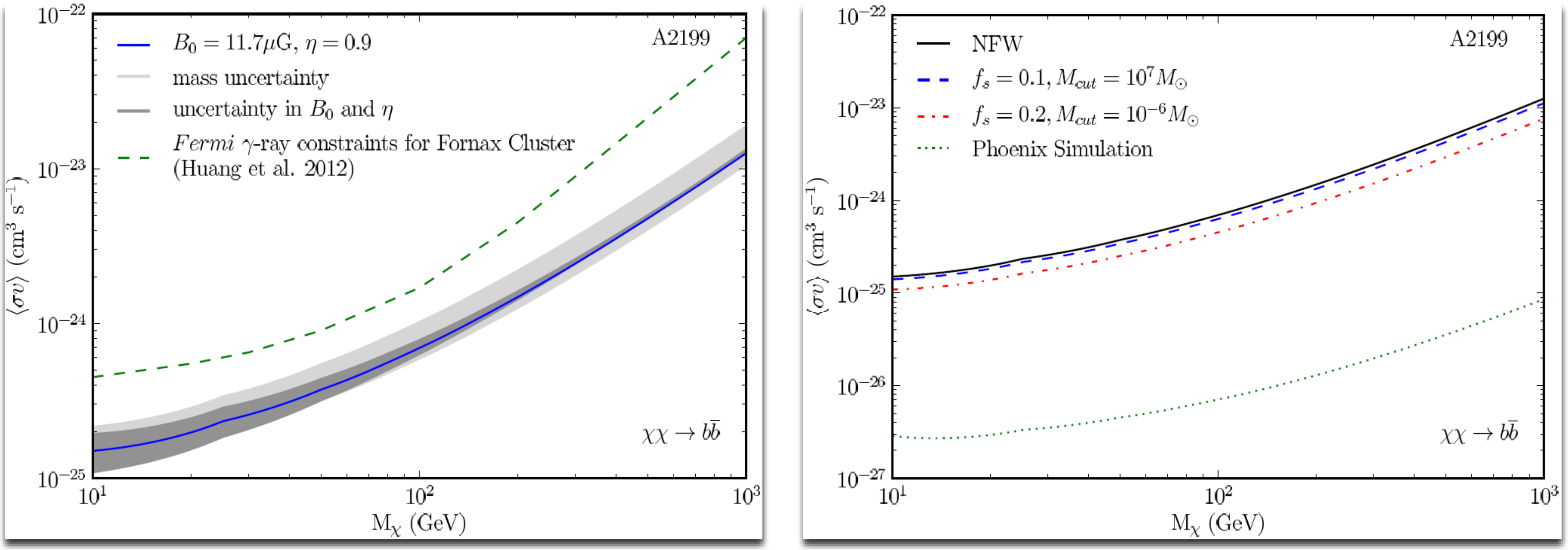
- Smooth NFW profile for ~ 10 galaxy clusters: comparable results for different clusters.
- Galactic center: similar limits. (arXiv:1002.0229)
- M31 galaxy: stronger bound by a factor of 10 (3) than A2199 for the bb ($\tau^+\tau^-$) channel.

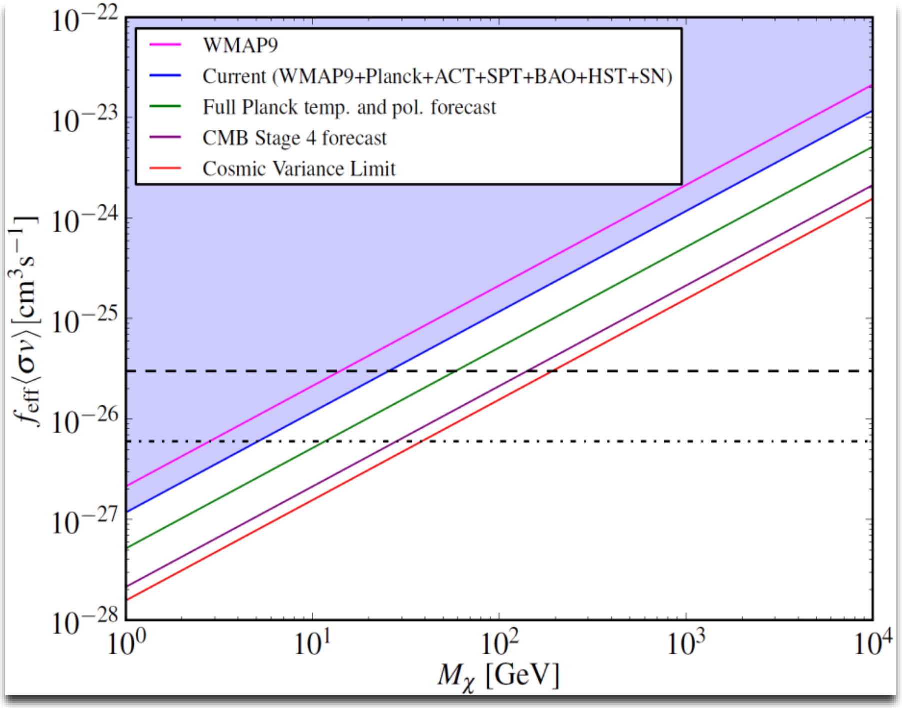
Indirect detection: radio II

Storm, Jeltema, Profumo & Rudnick arXiv:1210.0872



- Effects of uncertainty in the cluster M & B → a factor of ~2
- Clusters host various subhalos → radio emission limits on <σv> strongly depend on the assumed amount of cluster substructure
- Phoenix Project: a series of DM simulations of different galaxy clusters following the evolution of cluster-sized halos (arXiv:1201.1940)

Indirect detection: CMB

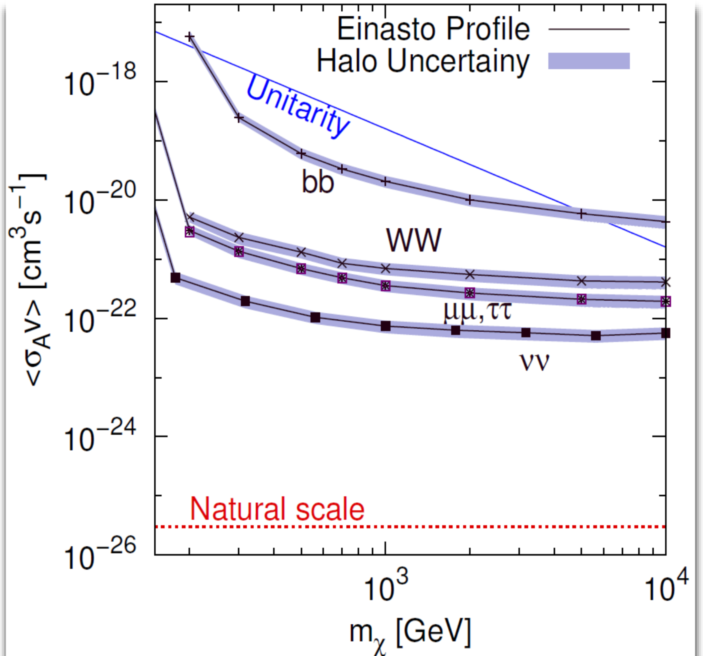


Madhavacheril, Sehgal & Slatyer, arXiv:1310.3815

- DM annihilations into SM particles → injecting E into the plasma → affecting recombination & reionization → modifications in the CMB
- Efficiency factor $f_{\rm eff}$: the fraction of the injected E by DM annihilations which is deposited in the plasma. Varying with SM particles.

Indirect detection: neutrino

IceCube, arXiv:1101.3349



- DM annihilations in Galactic halo are constrained by IceCube ν measurements
- But weak and only applicable for m_{DM} > O(100) GeV
- Capture & subsequent annihilations of DM in the sun would induce ν fluxes

  → bounds from Super-K & IceCube → highly model-dependent: σ^{anni}, $\sigma^{\chi N}$, $\sigma^{\chi\chi}$

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Direct detection I

Berlin, Hooper & McDermott, arXiv:1404.0022

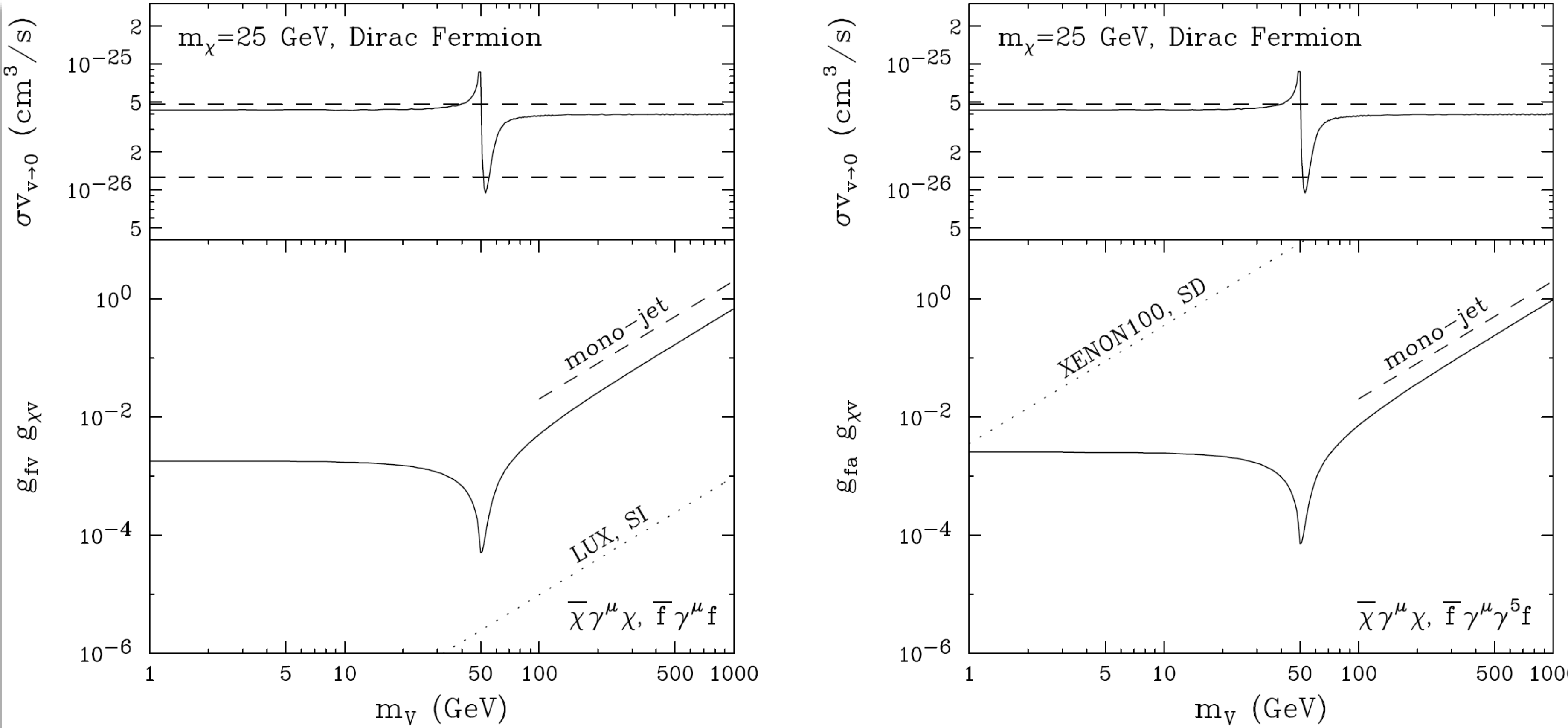
DM bilinear	*SM fermion bilinear*			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2$, $\sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2$, $\sigma_{\rm SD} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\boldsymbol{\sigma v \sim 1}$, $\boldsymbol{\sigma_{\rm SI} \sim q^2}$	$\boldsymbol{\sigma v \sim 1}$, $\boldsymbol{\sigma_{\rm SD} \sim q^4}$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1$, $\sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1}$, $\boldsymbol{\sigma_{\rm SD} \sim v_\perp^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\sigma v \sim v^2$, $\sigma_{\rm SI} \sim v_\perp^2$	$\boldsymbol{\sigma v \sim 1}$, $\boldsymbol{\sigma_{\rm SD} \sim 1}$

DM bilinear	*SM fermion bilinear*			
scalar DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\phi^\dagger\phi$	$\sigma v \sim 1$, $\sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1}$, $\boldsymbol{\sigma_{\rm SD} \sim q^2}$	–	–
$\phi^\dagger\overleftrightarrow{\partial_\mu}\phi$ (complex only)	–	–	$\sigma v \sim v^2$, $\sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2$, $\sigma_{\rm SD} \sim v_\perp^2$
vector DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$X^\mu X^\dagger_\mu$	$\sigma v \sim 1$, $\sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1}$, $\boldsymbol{\sigma_{\rm SD} \sim q^2}$	–	–
$X^\nu\partial_\nu X^\dagger_\mu$	–	–	$\sigma v \sim v^2$, $\sigma_{\rm SI} \sim q^2 \cdot v_\perp^2$	$\sigma v \sim v^2$, $\sigma_{\rm SD} \sim q^2$

- Model-dependent
- Stringent limits for only a few interactions

Direct detection I

Berlin, Hooper & McDermott, arXiv:1404.0022



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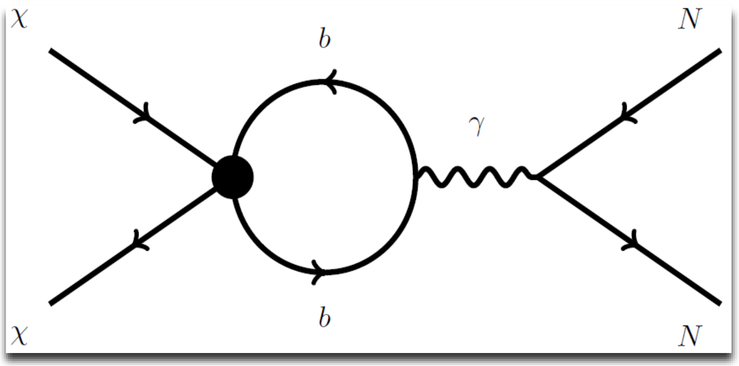
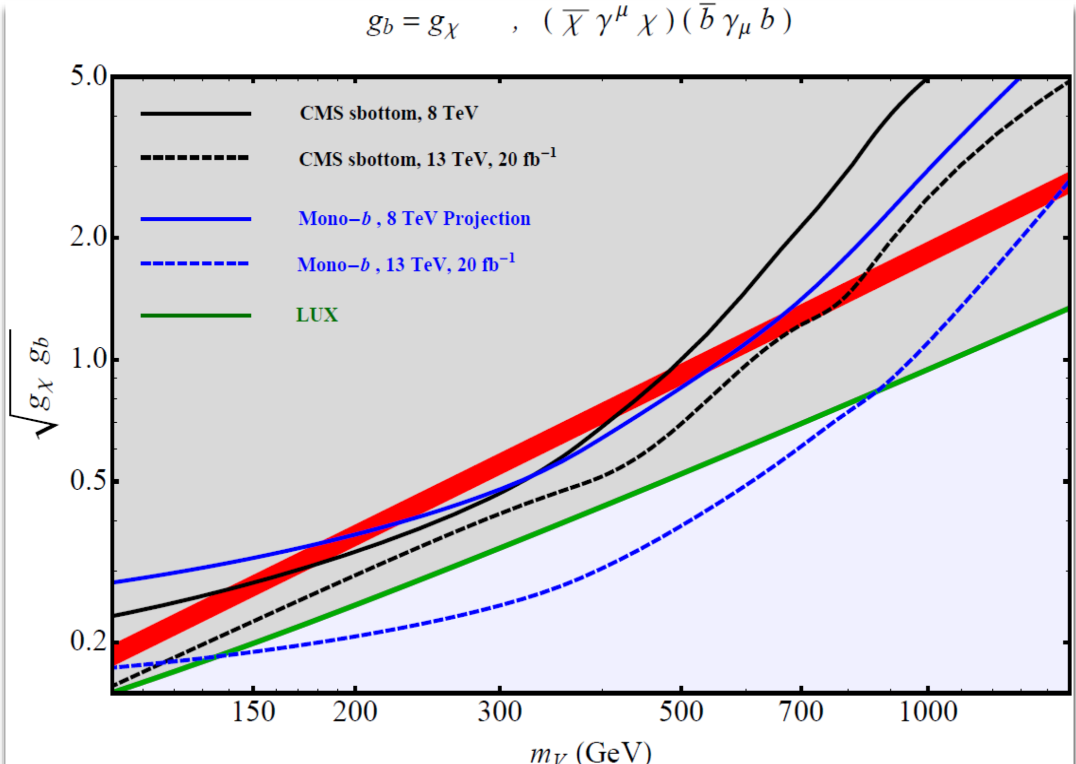
- Stringent limits for only a few interactions

Direct detection II

Izaguirre, Krnjaic & Shuve, arXiv:1404.2018





- Couplings to only b-quarks → weaker limit due to small heavy quark contribution
- But, b-loop induced scattering through a photon → still strong bounds

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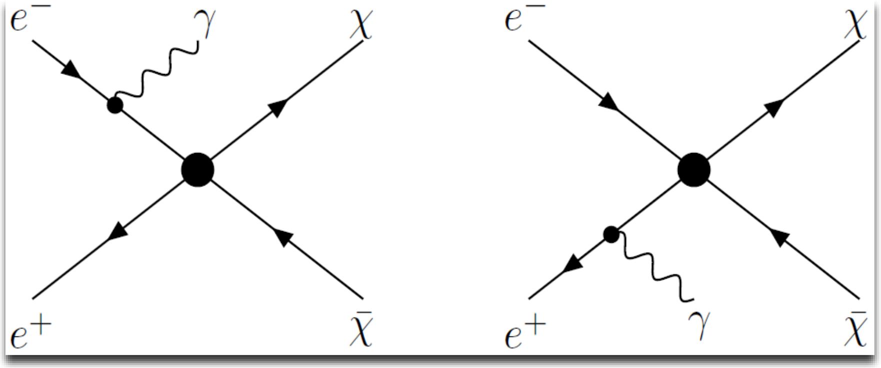
Collider: LEP & ILC I

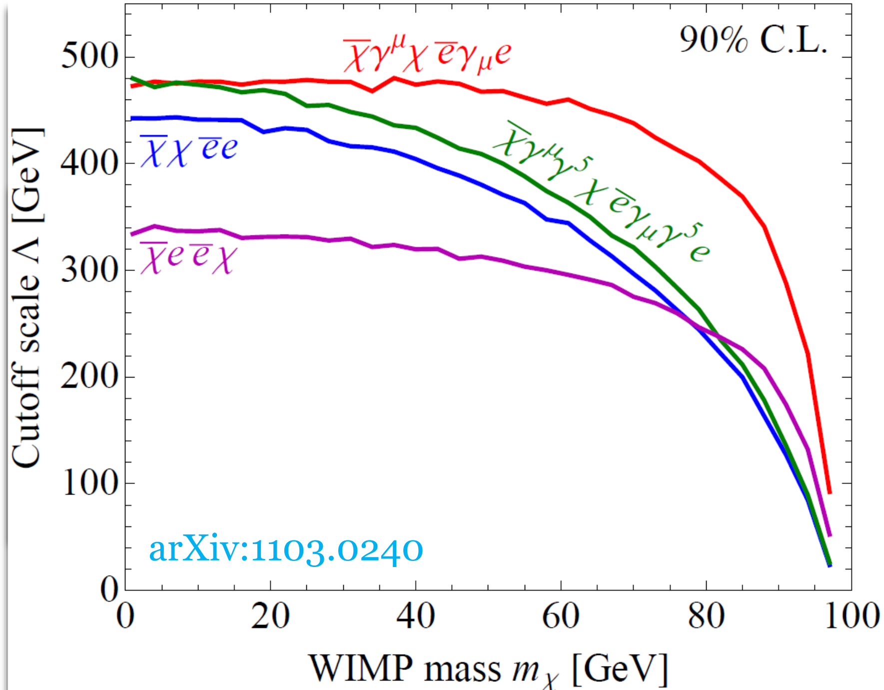
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)}{\Lambda^2}\,,$$
$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2}\,,$$
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma_5\ell)}{\Lambda^2}\,,$$
$$\mathcal{O}_t = \frac{(\bar{\chi}\ell)(\bar{\ell}\chi)}{\Lambda^2}\,,$$
$$\mathcal{O}_{PS} = \frac{(\bar{\chi}\gamma_5\chi)(\bar{\ell}\gamma_5\ell)}{\Lambda^2}$$



- LEP(ILC): mono-γ+E_T → limits on O_i → Compute $\langle\sigma v\rangle_{\chi\chi\to ee}$ using micrOMEGAs
- For illustration, we choose O_V. (O_S & O_A: suppressed s-wave)
- O_t: better by a factor of ~2. O_{PS}: weaker by a factor of ~4 (arXiv:1211.2254)
- LEP constrains parameter space for e-channel significantly, but still OK.

Collider: LEP & ILC I

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)}{\Lambda^2},$$
$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2},$$
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma_5\ell)}{\Lambda^2},$$
$$\mathcal{O}_t = \frac{(\bar{\chi}\ell)(\bar{\ell}\chi)}{\Lambda^2},$$
$$\mathcal{O}_{PS} = \frac{(\bar{\chi}\gamma_5\chi)(\bar{\ell}\gamma_5\ell)}{\Lambda^2}$$



- LEP(ILC): mono-γ+E_T → limits on O_i → Compute $\langle\sigma v\rangle_{\chi\chi\to ee}$ using micrOMEGAs
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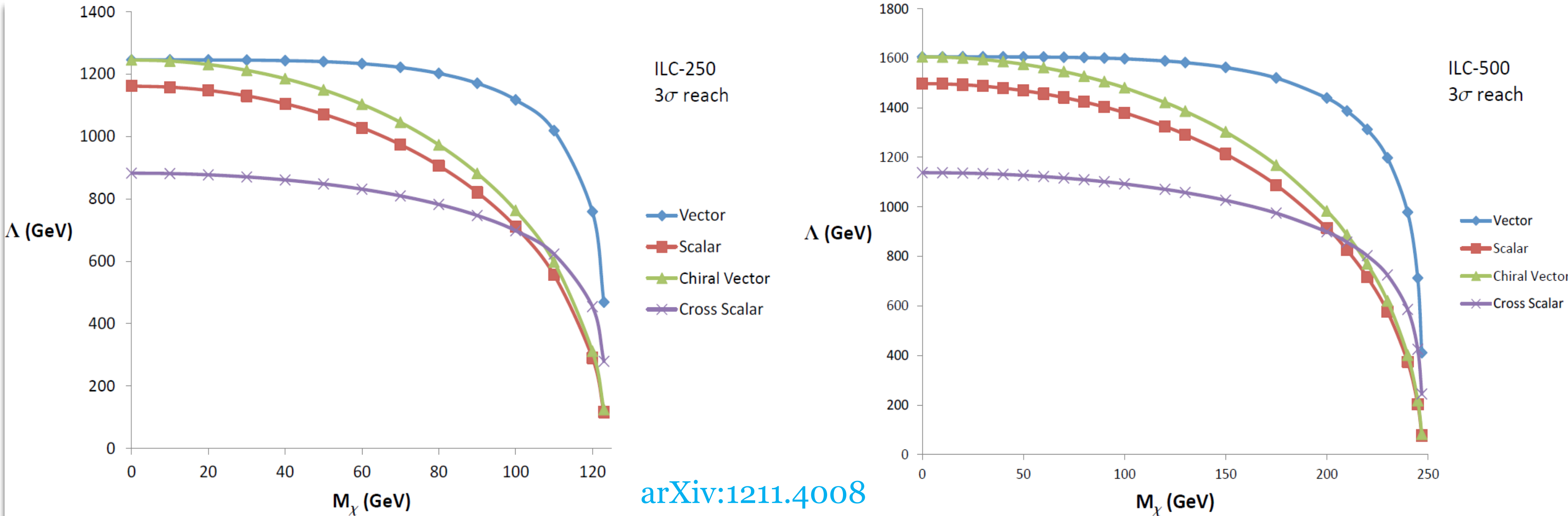
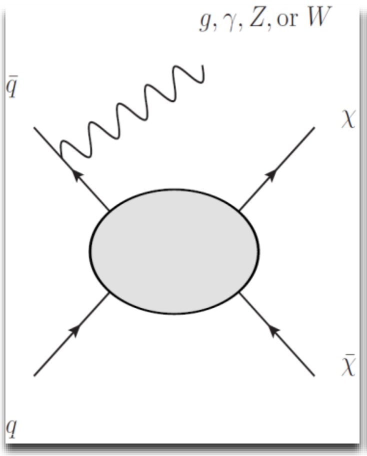
Collider: LEP & ILC II

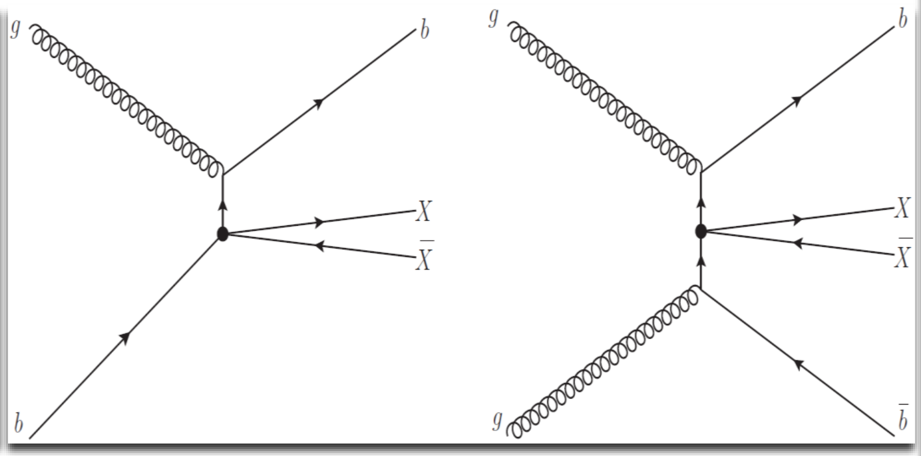


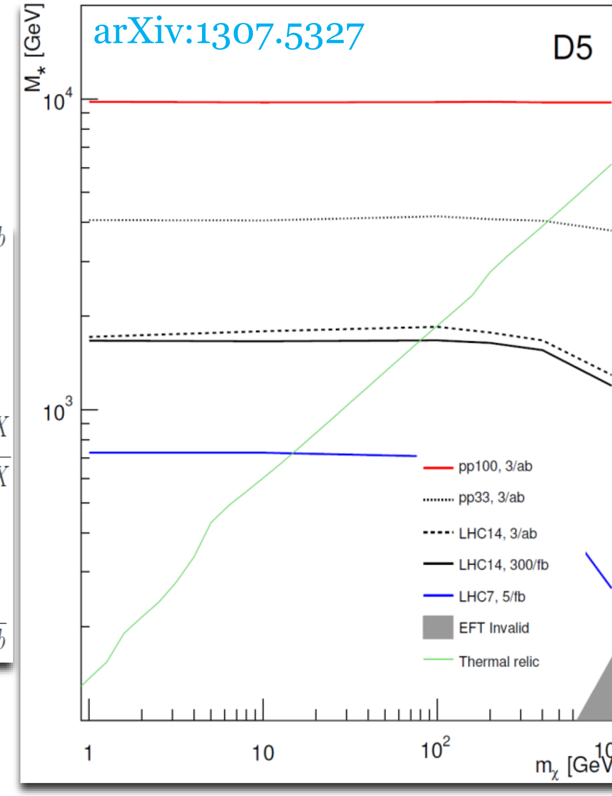
arXiv:1211.4008

- ILC(250 GeV & 250 fb^{-1}): 2.5-3 higher Λ → O(10^{1-2}) improved limits on $\langle \sigma v \rangle_{\chi\chi \to ee}$
- ILC(500 GeV & 500 fb^{-1}): a factor of ~4 improvement

Collider: LHC



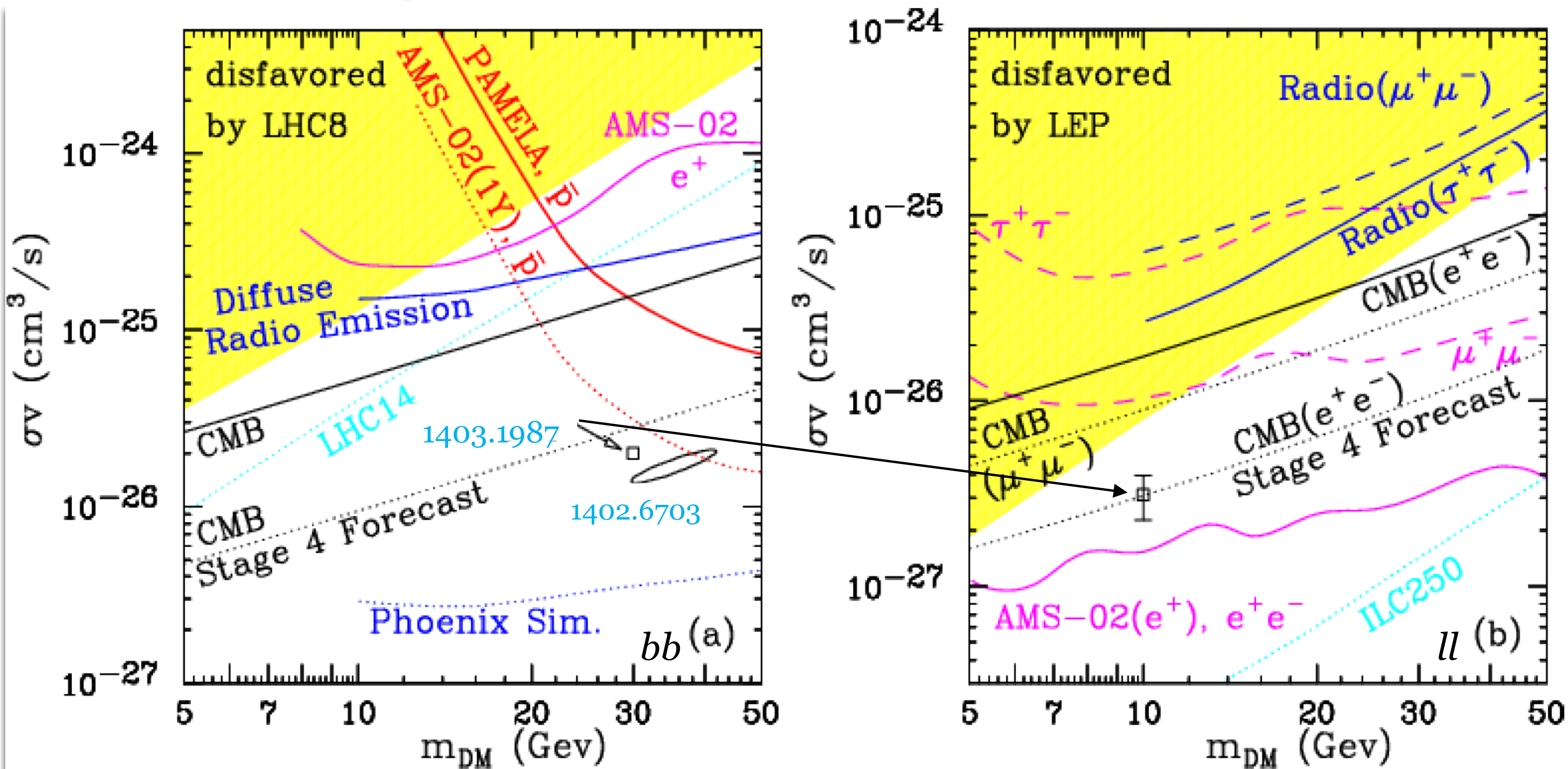




- mono-j+E_T → powerful limits.
- b, t-quarks flavored DM: mono-b+E_T becomes more effective.
- Using CMS data and results of 1307.5327 & 1303.6638 → limits on O_i → Compute $\langle \sigma v \rangle_{\chi\chi \to bb}$ using micrOMEGAs
- LHC14: projected limits at 95% CL with 100 fb^{-1}

Summary of constraints I

K.C. Kong & JCP, arXiv:1404.3741

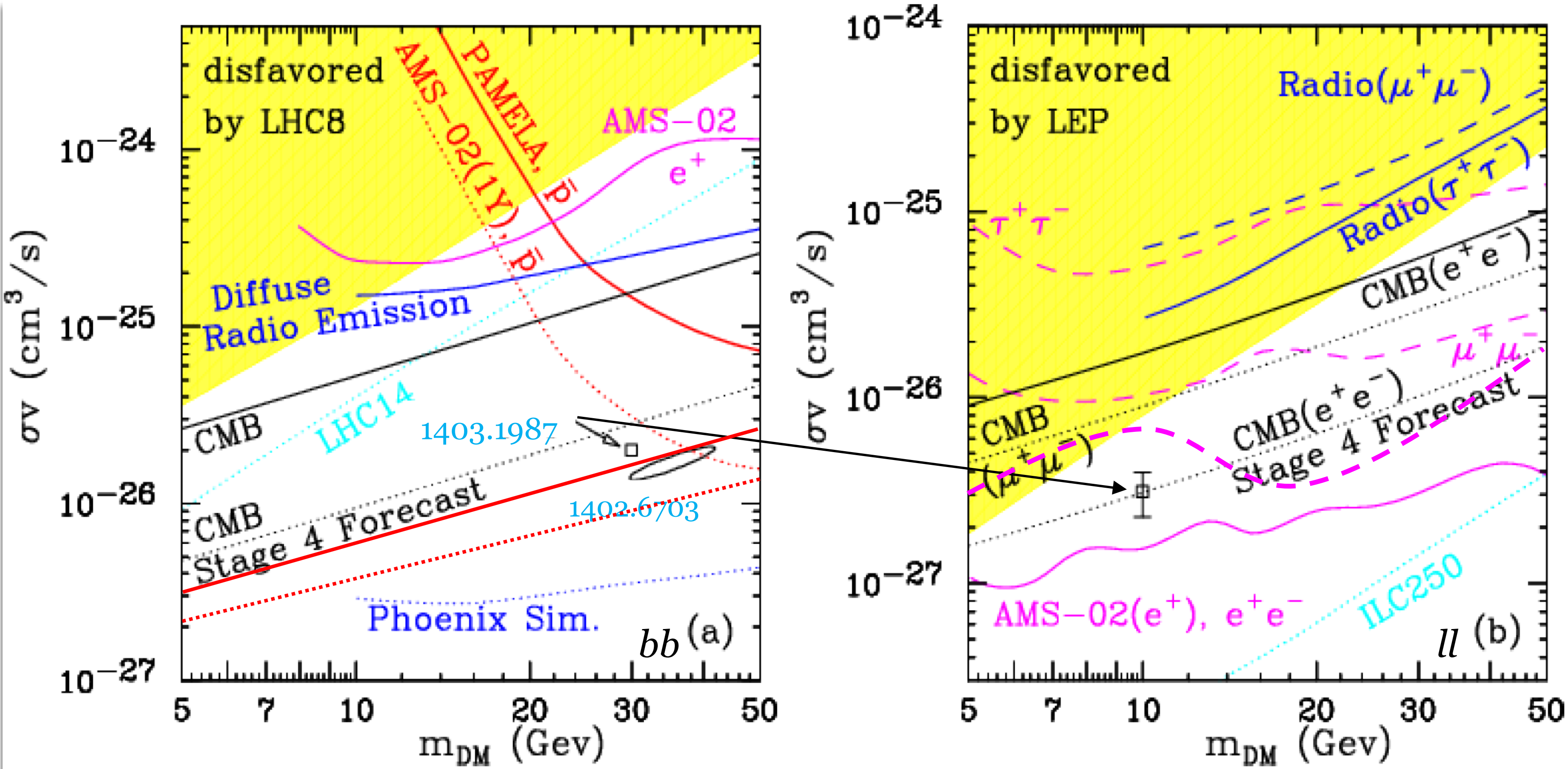


- Limits on $<\sigma v>_{\chi\chi \rightarrow XX}$: e^+&anti-p fluxes, diffuse radio, CMB, colliders. (Dotted: projected sensitivities)
- A rescaling factor of 1/3 is taken into account for democratic annihilations into leptons in (b)

  → The same $<\sigma v>$ is applied to each leptonic channels.

Summary of constraints I

K.C. Kong & JCP, arXiv:1404.3741



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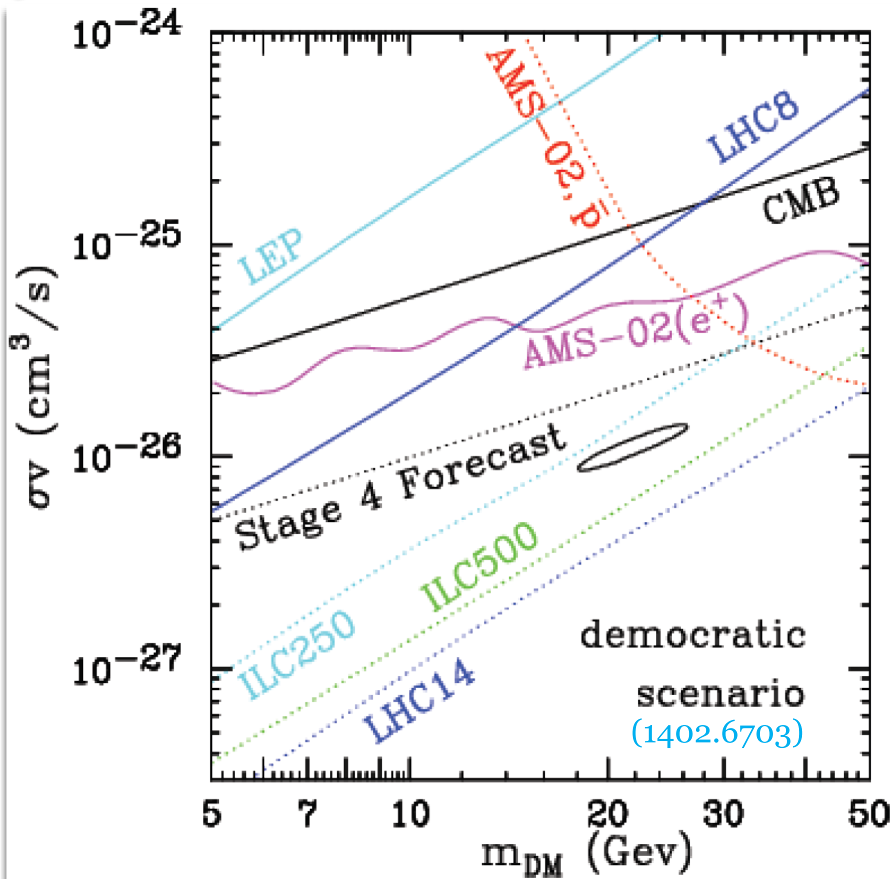
Summary of constraints II

K.C. Kong & JCP, arXiv:1404.3741

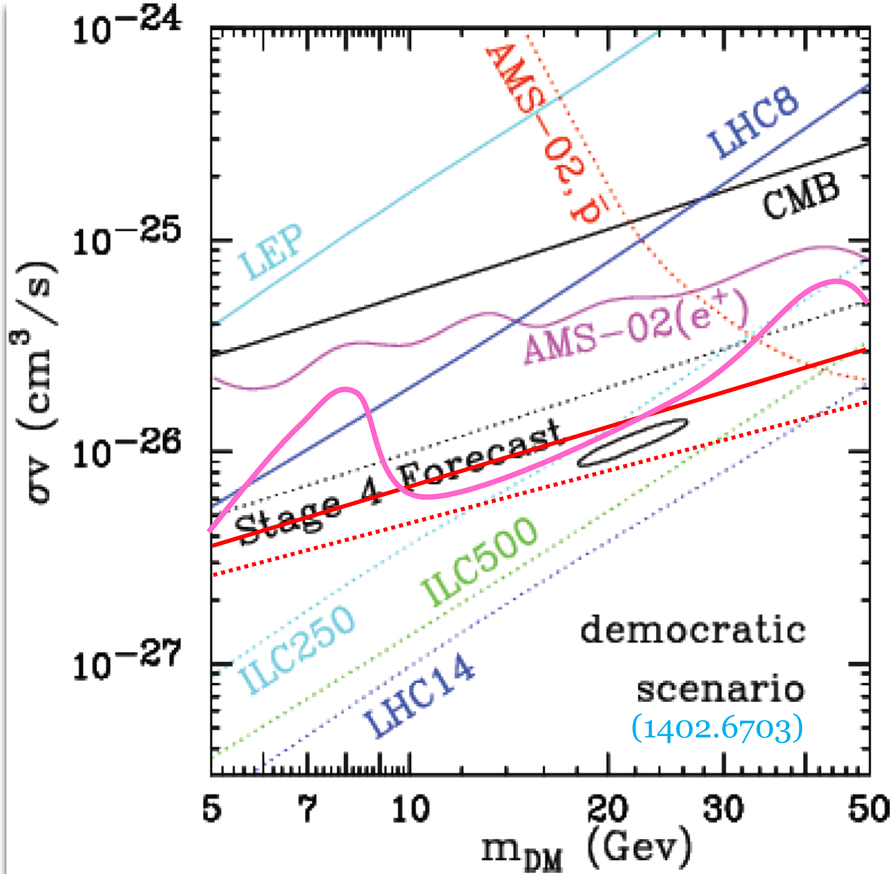


- All kinematically accessible SM fermions, l:ν:q=1:1:5

→ Each bound is rescaled by the corresponding annihilation fraction.

Summary of constraints II

K.C. Kong & JCP, arXiv:1404.3741

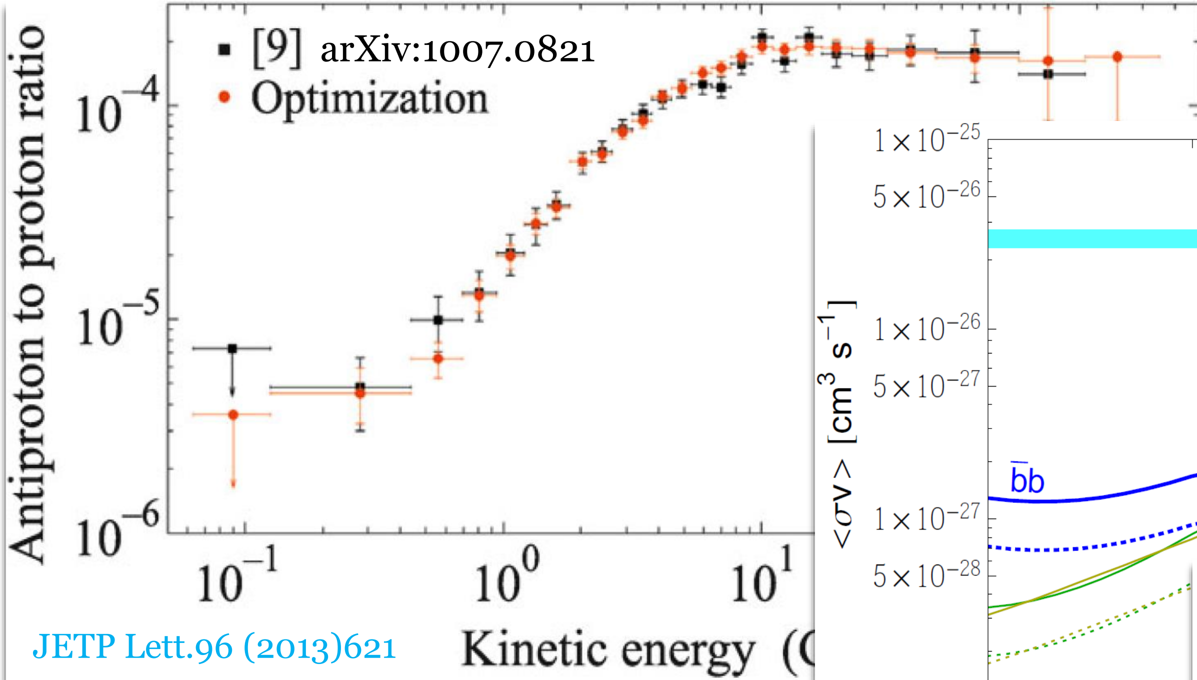


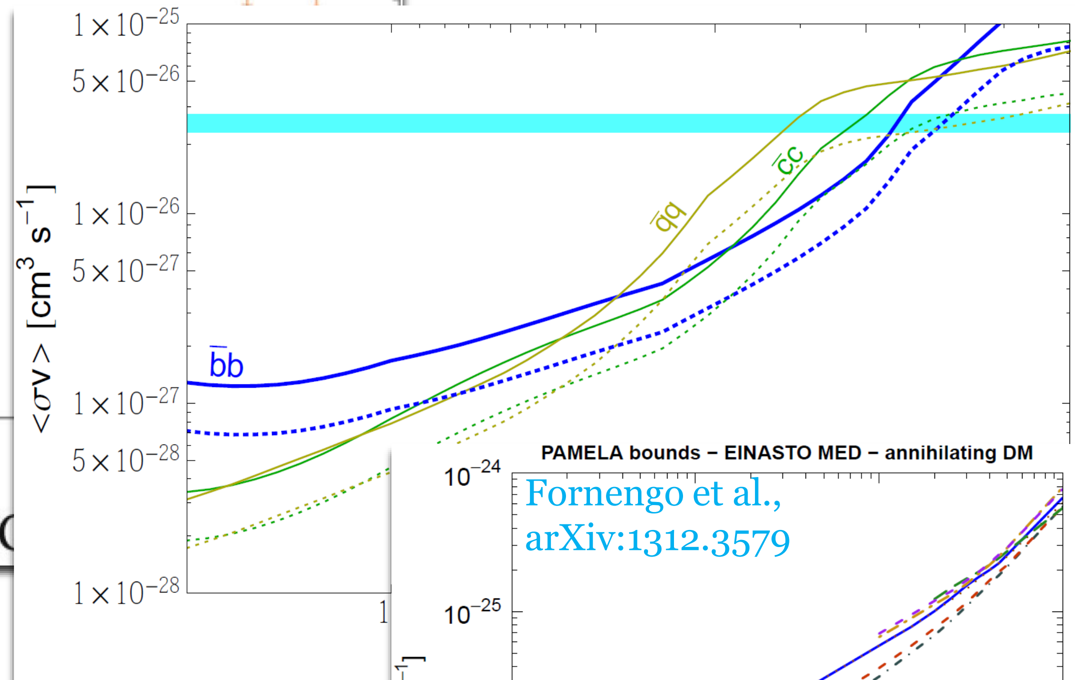
❖ All kinematically accessible SM fermions, l:ν:q=1:1:5

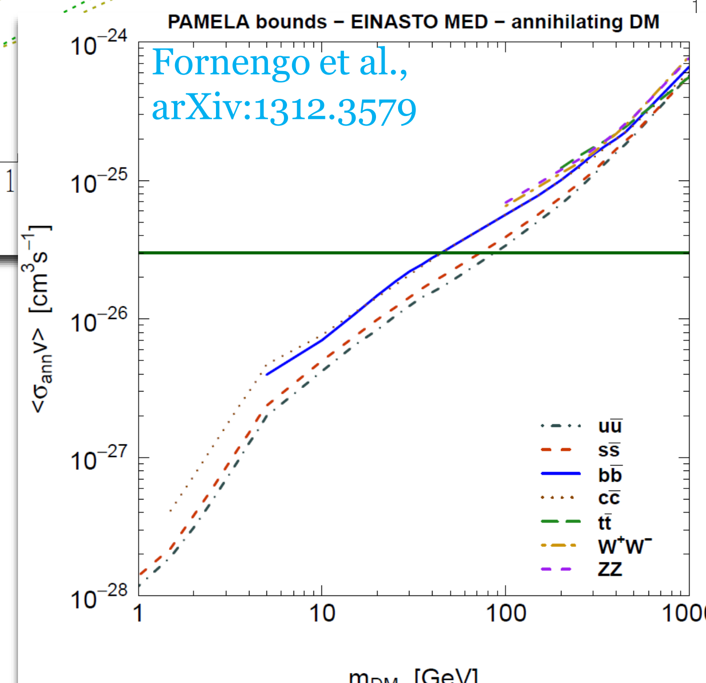
→ Each bound is rescaled by the corresponding annihilation fraction.

Updated limits from anti-p

Bringmann, Vollmann & Weniger, arXiv:1406.6027







- Improvements by a factor of 2-5
- Use the recently published update of PAMELA data
- Improved statistical treatment of the BG uncertainties

Outline

- DM indirect searches
  - → GeV γ-rays from the Galactic center
- Constraints:
  - ✓ Indirect detections
  - ✓ Direct detections
  - ✓ Colliders
- Conclusion

Conclusion

- GeV γ-ray excess around the GC from the Fermi-LAT data
- $<\sigma v>_{bb}=(1\text{-}2)\cdot 10^{-26}\ cm^3/s$ for m_{DM}=30-40 GeV,

  $<\sigma v>_{ll}=(0.6\text{-}1.2)\cdot 10^{-26}\ cm^3/s$ for m_{DM}=10 GeV
- Constrains from PAMELA, AMS-02, CMB, IceCube, LEP, LHC, …

$\boxed{\rightarrow \text{favor DM couplings to (2}^{nd}\text{) 3}^{rd}\text{ generation of SM fermions (}l^-l^+\text{).}}$

:lepton channels: e+ & LEP, quark channels: anti-p, LHC & LUX

- Near future: AMS-02 (anti-p), LHC14

  Far future: ILC, CMB, …

Thank you